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Rockets, Motor Cases
Titanium Fabrication
Titanium Alloys

Tenth Quarterly Report on Research and Development of Titanium Rocket Motor Case

By

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FOREWORD

This interim technical report was prepared by the Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford, Connecticut in compliance with Contract No. DA-19-020-ORD-5230. It covers technical accomplishment on the research and development of titanium rocket motor cases for the three-month period from October 1 through December 31, 1962.

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I. INTRODUCTION

A. Purpose and Scope of Project

This program is aimed at the development of a high strength, lightweight, titanium alloy pressure vessel of the type used for solid fuel rocket motor cases. B-120 VCA titanium alloy has been selected for further investigation because of its inherent high strength, its potential of reliably exceeding the yield strength/ density ratio of 1,000,000 inches and the possibility of reaching 1,200,000 inches. The main problems involved in its application include the development of fabrication techniques to achieve consistently high strength levels along with the most economical use of material.

B. Subject Matter Covered In This Report

A brief summary of the work completed to date and during the past calendar year (January 1, 1962 through December 31, 1962) is included. The results of current investigations are reported and the future work planned under the various phases of the program is outlined. Reported results of recent research include the following:

1. Smooth and notched (K_t=8) tensile properties (-40 to 400F) of flow-turned material with hydrogen contents of 70 and 200 ppm,

2. Results from cyclic loading and tensile testing (70F) of B-120 VCA titanium alloy TIG welds,

3. Tensile and hardness data (70F) for Ti-6Al-6V-2Sn alloy TIG welds,

4. Smooth and notched (K_t=8) tensile data (70F) for full scale 40-inch diameter roll-forged rings re-solution treated at 1800F,

5. Smooth and notched (K_t=8) tensile properties (70F) of subscale 14-inch diameter and full scale 40-inch diameter flow-turned cylinders,

6. Tensile properties of a full scale 40-inch diameter rear dome press-forged in closed dies at 1750F,

7. Results from hydrostatically burst testing full scale component assemblies, one containing a flow-turned cylinder and the other a press forged rear dome, and

8. Bend and tensile test data (70F) for Ti-15 Mo alloy sheet stock in the solution treated, and solution treated and aged conditions.

The above results are discussed and tentative conclusions drawn.

II. SUMMARY OF PREVIOUS WORK COMPLETED

The work which has been completed under each phase since the initiation of the program and during the past calendar year (January 1, 1962 through December 31, 1962) is described. Metallurgical factors which influence material response to fabrication techniques and heat treatment have been investigated. The most economical use of material (reduced input weight and thinner sections) has been emphasized during the forging phases of the program. The status of material which has been and is currently being used in the program is outlined in Table I.

A. Effects of Interstitials

1. Hydrogen - The effects of hydrogen content on delayed cracking and stress-corrosion have been studied with emphasis on the flow-turned material to be used in motor case cylindrical sections. The present Pratt & Whitney Aircraft specification calls for a maximum hydrogen content of 0.015 per cent (150 ppm). A cathodic hydrogenation technique has been developed to yield reproducible hydrogen contents at the 200 ppm level. An evaluation program has been conducted on cold-rolled and aged sheet stock at the 70 and 200 ppm hydrogen levels and on flow-turned material at the 240 ppm level. Investigation to date has shown no detrimental effect of hydrogen on notched (K_t=8) tensile behavior at the standard strain rate (0.005 inch/inch/minute) or under sustained loads over the temperature range from -35 to 400F.

   During the past year, two 14-inch diameter rolled rings diverted from the ring rolling development phase have been vacuum-annealed (1400F) to provide material for evaluation at two hydrogen levels (approximately 70 and 200 ppm). The first of these rings has been flow-turned and the aging response tensile properties have been determined. Results showed poor ductility which was attributed to cracking of the inside surface of the flow-turned cylinder. To alleviate this condition, the second rolled ring was re-solution treated at 1800F before flow-turning. Smooth and notched (K_t=8) tensile tests have been conducted over the -40 to 400F temperature range (70 and 200 ppm hydrogen) and results appear in this report in the section on test results, page 17.

2. Oxygen - The effects of oxygen content on aging response, notch sensitivity, and stress corrosion susceptibility were determined using six press-forged pancakes with nominal oxygen contents of 0.10, 0.15, and 0.20 per cent. This work was completed during 1961. Testing was conducted at both room temperature and at -40F. Results of this testing indicated that satisfactory aging to the 200,000 psi yield strength level with retention of maximum ductility required an oxygen content in the range of 0.11 to 0.17 per cent with best results being achieved with 0.13 per cent oxygen. No significant degradation in notched (K_t=8) tensile or stress-corrosion sensitivity was noted in the 0.10 to 0.20 per cent oxygen range.

B. Forging Practice

The forging phase of this program has been aimed primarily at the improvement of mechanical properties in forged end closures with maximum economy. Closed die press-forging has resulted in savings by requiring lower forging input weights and by using a less expensive forging and machining sequence.

1. Press Forging - Seven pancakes were forged on open dies at Wyman-Gordon using both high and low strain rates at 1600, 1700, 1850, and 2000F. The experiment was designed to determine the effects of strain rate and forging temperature on aging response and uniformity in terms of mechanical properties. These pancakes were evaluated for aging response and smooth and notched (K_t=8) tensile property uniformity at the 180,000 psi yield strength level. None of these pieces was capable of attaining the 200,000 psi yield strength level, apparently due to the relatively low oxygen content of approximately 0.10 per cent. Results of this work indicated that maximum ductility was attained by minimizing the forging temperature and strain rate to produce a correspondingly low finishing temperature.

Wyman-Gordon has also forged nine subscale 14-inch diameter domes in closed dies using the dogbone and the pancake and preform techniques. These subscale domes were forged in order to apply the knowledge gained from forged pancakes to subscale forged domes and to further establish the optimum forging temperature range and subsequent heat treatment. The three domes made by the dogbone method were forged at 1650, 1700, and 1850F during the final operation. Five pancake and preform domes were forged at the same temperatures and one piece was upset at 2000F directly from billet stock. These domes have been evaluated for both aging response and for smooth and notched (K_t=8) tensile property uniformity. Direct aging at 800, 850, and 900F and aging at 900F following 1400 to 1450F solution treatment were evaluated. From this study it was again concluded that lower forging temperatures were desirable for maximum aged ductility, but that higher temperatures (1850F and above) would result in improved uniformity of properties. In addition, it was found that optimum tensile ductility following forging at relatively low temperatures (1650 to 1700F) resulted from direct aging at 900F, but that following forging at higher temperatures an interim solution treatment at 1450F before aging was required.

At this point, development efforts were extended to the press-forging of full scale domes in closed dies by Wyman-Gordon. A total of eleven 40-inch diameter domes (six front and five rear) have been forged to date. During this period, forging techniques were sequentially developed for front and rear domes now being prepared for individual hydrostatic burst testing. Five of these pieces (three front and two rear) were forged and evaluated during 1961. The remaining three front and three rear domes have been forged and evaluated since January 1, 1962. Mechanical properties of the final piece (rear dome ELA-9) are presented in this report in the section on test results, page 16. Typical tensile properties now attainable are 180,000 psi minimum yield strength with 3.5 to 4.0 per cent minimum elongation. Variations, primarily with composition as a function of original ingot location, can occassionally produce lower tensile properties with an absolute minimum of a 175,000 psi yield strength with 3.0 per cent elongation.

The first front dome (EJO-1) was forged in three operations at 1700F by the pancake and preform method, using the dies normally employed for second stage Pershing steel domes. This dome did not fill the dies during the final 1700F operation and was therefore restruck in the same dies at 1900F. The resulting part showed very poor ductility after either direct aging or solution treating and aging. This was apparently due to the high restrike temperature and low reduction.

The second front dome (ELA-3) was therefore forged in three steps at 1850F in the closed dies fabricated under this contract. This part also demonstrated low aged ductility. This low ductility was attributed to a long furnace soaking time before final closed die forging and to inadequate reduction especially toward the polar region. To eliminate these two factors, the third dome (ELA-4) was also press-forged in three steps at 1850F but with minimum intermediate heating times, and with a plug trepanned from the preform center to permit increased metal flow toward the polar boss. Test results, however, showed no significant ductility improvement as compared with the previous part.

Based on the above results, it was concluded that satisfactory ductility (4 per cent minimum tensile elongation) could not be achieved at the 180,000 psi yield strength level without either greater reduction at 1850F or a lower forging temperature. Die modifications were therefore made to increase flow toward the skirt regions. The next front dome (ELA-5) was closed die forged in the final operation at 1750F. The mechanical properties of this piece, however, were only slightly better than those of the previous two domes forged at 1850F. Because no further reduction in forging temperature was possible, it was decided to accept the resultant properties (175,000 psi minimum yield strength in the noncritical polar region with 3.0 to 3.5 per cent minimum elongation at the skirt) and to burst test this dome. In addition, two more front domes (ELA-7 and EJO-2) were forged by this method but forging practice included refinements of the in-process heat treatment developed by Wyman-Gordon. Properties of these parts were similar to those of the previous dome (ELA-5) with no improvements noted as a result of Wyman-Gordon's modification. These parts are to be employed for full scale motor case fabrication.

Rear dome forging development has followed a development similar to that described for front domes. The first rear dome (ELA-2) was forged in three steps at 1850F by the dogbone technique but showed poor aged ductility. Subsequent preform and die modifications permitted final closed die forging of the second dome (ELA-1) at 1800F and a resultant increase in ductility. It was found that this part essentially attained the desired minimum properties after aging (180,000 psi yield strength, 4.0 per cent elongation) and therefore it has since been decided to utilize this dome for the full scale motor case.

To further improve aged ductility, the rear dome dies were modified similarly to the front dome dies to permit increased metal flow into the skirt or rim areas. Another rear dome (ELA-6) was then press-forged with the final closed die operation conducted at 1750F. Test results showed satisfactory properties similar to those of the previous dome (ELA-1) and this part was therefore machined and burst tested with excellent results. These results are reported in the section on test results, page 20.

Based on the above results, two additional rear domes (ELA-8 and ELA-9) were forged by this technique (three steps at 1800, 1800 and 1750F). Processing of dome ELA-9 included the Wyman-Gordon heat treatment refinement mentioned previously. Both of these parts showed slightly inferior properties (175,000 psi minimum yield strength with 3.0 per cent minimum elongation). The decrease in tensile properties is believed to be a result of composition variations (oxygen and chromium contents) associated with original ingot location. One of these domes (ELA-8) is to be machined for individual burst testing to establish the performance which results from these properties which are considered to be at the low end of the forged component scatter band.

2. <u>Hammer Forging</u> - Hammer forging has been investigated as an alternative means of producing domes. It was initially believed that hammer forging would impart more work to the part than would press forging as a result of its higher strain rate. Ladish hammer-forged four pancakes which were evaluated for aging response and uniformity of tensile properties. Tensile ductility exhibited by these pieces was lower than comparable press-forgings and further work was therefore not conducted. This investigation was completed during 1961.

3. Ring Rolling - The ring rolling phase of the program has been designed to develop rolling techniques which will produce the optimum flow-turnability and subsequent mechanical properties. The sixteen subscale 14-inch diameter rings intended under this phase have been rolled by Ladish. The first six rings were rolled in single and in multiple operations at temperatures from 1800 to 2000F and have been evaluated in the solution-treated condition and after flow-turning by the previously used two-pass technique with 50 per cent reduction per pass.

Based on results from the first six subscale rings, the remaining ten rings were rolled in a single operation at 1900F. All ten of these rings have been flow-turned, four during the 1962 calendar year. The last two of the subscale flow-turned cylinders are now being evaluated.

Also based on results from the subscale rings, seven full scale 40-inch diameter rings were rolled by Ladish in multiple operations at 1900F. Machine limitations prohibited rolling in a single operation. Six of these rings were received at Pratt & Whitney Aircraft during 1961 and the remaining ring was received during 1962. All rings were evaluated for solution treatment during 1962. Resolution treatment at 1800F after an initial heating at 1450F was found to produce optimum flow-turnability.

C. Flow-Turning Development

In conjunction with the roll forging development program, subscale 14-inch diameter roll forged rings have been flow-turned in order to determine the forging practice which will produce the optimum material properties for flow-turn blanks. After machining the roll forged rings into blanks, the rings were flow-turned in two passes with 50 per cent reduction per pass. The resulting wall thickness was 0.080 inch. Flow-turning parameters were held constant so that the effects of variations in the forging technique could be evaluated. All of the cylinders grew radially during both passes and local bulging occurred during the second pass. Although slight variations in metallurgical properties resulted from changes in forging practice, it was found that these changes resulted in no significant differences in behavior during flow-turning.

Rolled and welded 9.4- and 14-inch diameter blanks have been flow-turned to provide basic evaluation of the effects of roller geometry, mandrel speed, reduction and feed rate on radial growth and local bulging. Subscale 14-inch diameter roll-forged rings have been flow-turned to further evaluate the various parameters and to optimize the flow-turning operations before flow-turning full scale roll-forged rings. The use of two sizes of subscale rings allowed determination of the changes in flow-turning performance which could be anticipated in proceeding from subscale to full scale rings. The starting condition of the roll-forged rings was optimized through solution heat treatment. Significant improvement of the flow-turnability of the B-120 VCA titanium alloy was achieved and no adverse effects on the aging response or aged properties resulted.

The subscale phase of the flow-turning program has, therefore, been completed and the flow-turning techniques developed are now being utilized to form full scale rocket motor case cylindrical center sections from roll-forged rings. Seven full scale cylindrical center sections will be flow-turned with 0.140-inch thick weld lands at both ends and with a thin central membrane thickness of 0.070 inch.

D. Weld Development

The weld development phase is aimed primarily toward the improvement of weld quality and fracture toughness. Initial work on the establishment of weld quality and toughness techniques was concluded in 1961. Evaluation of alternate filler materials has also been completed. Multiple-pass TIG-welding studies are continuing. An improved copper-fixturing technique was developed which greatly reduced weld porosity and which produced more uniform weld penetration.

Cyclic testing has been and is presently being employed as the basic weld evaluation method to determine the characteristics of crack initiation and growth at weld porosity. Cracking of this type has been observed in pressure vessel circumferential welds. The cycle test of a specimen containing a longitudinally-disposed weld bead is designed to simulate motor case stress and loading conditions with a three-cycle proof test (80,000 psi stress) followed by additional cycles at increasing stress levels (5000 psi increments) until failure. Radiographic inspection after each cycle enables determination of the extent and nature of cracking. Multiple-pass TIG welds, welds made with alternate filler materials, welds made by the improved fixturing technique, electron beam welds and weld repairs have been evaluated using this test technique. Testing of B-120 VCA TIG welds is presently being completed. TIG welds on AISI H-11 steel and Ti-6Al-4V alloy have also been cyclically tested so that their behavior may be compared. A total of approximately 60 of these cyclic specimens have been tested to date, 40 during 1961 and an additional 20 during 1962. Cyclic tests are being used to qualify the TIG-welding schedule employed for full scale motor case fabrication. Presently, it appears that the radiographic specification used for Pershing steel motor cases can be applied to full scale B-120 VCA titanium alloy circumferential weldments.

Hamilton Standard electron beam welds of various widths made at various travel speeds were evaluated for quality and mechanical properties including fracture toughness during 1961. Since no significant improvement in quality or toughness as compared to TIG welds was observed, no further evaluation of this weld technique was conducted.

During 1962 an investigation of the weldability and resulting mechanical properties of Ti-6Al-6V-2Sn alloy was initiated to determine the suitability of the alloy for rocket motor case applications.

Rolled rings of the alloy were solution-treated and machined into 20-inch diameter circumferential weld samples. TIG weld studies and mechanical property evaluation have almost been completed. Results to date indicate that satisfactory weld ductility (greater than 5 per cent tensile elongation) cannot be achieved by either post weld annealing (100,000 to 130,000 psi yield strength) or 1100F age-weld-age sequences (180,000 psi yield strength). Solution treating and aging (1000 to 1100F) after welding also produced poor ductility.

E. Metallographic Examination

Battelle Memorial Institute has completed electron microscope and microprobe analyses of press forged, flow-turned, and TIG- and electron beam-welded samples. The analyses were conducted in order to correlate mechanical properties with microstructure and with short range composition variations such as alloy segregation or depletion in the vicinity of grain boundaries. The primary results of these studies were as follows:

1. Poor flow-turnability was associated with a tendency toward etch pitting at the grain boundaries. This pitting may possibly be a result of alloy segregation.

2. The relatively sluggish aging response and poor ductility of regions in pancake forgings were found to be a result of factors other than coarse particle size. The sluggish aging response resulted from low density of the alpha aging constituent and the poor ductility resulted from alpha-lean areas adjacent to the grain boundaries.

3. The microstructures of TIG and electron beam welds were found to be similar with neither type exhibiting significant amounts of the grain boundary constituent.

F. Full Scale Components

1. Cylindrical Center Sections - The seven roll forged rings were re-solution heat treated at 1800F and machined into flow-turn blanks. Two rings were flow-turned of which one was aged to a 180,000 psi yield strength level. The part was welded to burst test adapters, instrumented with strain gages and hydrostatically tested to burst with failure at 1184 psig pressure.

2. Front Domes - Front dome ELA-5 has been machined and welded to a burst test adapter. The dome is currently being instrumented with strain gages prior to hydrostatic burst testing.

   Front dome ELA-7, which is scheduled for full scale motor case fabrication, was heat treated and is being rough machined.

   Front dome EJO-2 is being held for future consideration.

3. Rear Domes - Rear dome ELA-1, which is scheduled for full scale motor case fabrication, was forged, (see Technical Report No. WAL 766.2/1-6) solution heat treated at 1450F for 30 minutes, and aged at 900F for 20 hours.

Rear dome ELA-6 has been machined, welded to a burst test adapter, instrumented with strain gages, and burst tested. The strain gage data is under evaluation. The dome has been inspected to determine distortion patterns and is being sectioned to evaluate properties throughout the membrane section.

Rear dome ELA-8 did not meet the minimum tensile requirements although forged by the same technique (1800, 1800, and 1750F) as rear dome ELA-6 (which did meet the requirements). Rear dome ELA-9 was also forged at 1800, 1800 and 1750F, but the process included modifications used for the last two front domes. Tensile tests for ELA-9, however, have indicated a slow aging response and low tensile ductility in the skirt area. The tensile properties of ELA-9 are similar to those of ELA-8. As a result, it has been decided to machine and burst test rear dome ELA-8 as a component to determine the burst performance of a rear dome with a minimum yield strength of 175,000 psi and a minimum tensile elongation of 3 per cent. Rear dome ELA-9 will be held for future consideration.

G. Evalutation of Ti-15 Mo Alloy

Two sheets (each 36 x 24 x 0.075 inches) of Ti-15 Mo alloy were received for evaluation during 1962. Mechanical properties have been determined for the as-received (solution treated), and for the solution treated and aged conditions.

III. CURRENT TEST RESULTS AND FABRICATION STATUS

A. Effects of Interstitials (Hydrogen)

Smooth and notched (K_t=8) tensile properties have been determined at -40, 70 and 400F for the second 14-inch diameter roll-forged ring which had been vacuum-annealed at 1400F, re-solution treated at 1800F, and flow-turned by the present two-pass technique (50 per cent reduction each pass). Axial and circumferential specimen blanks were cathodically hydrogenated to the 200 ppm level. These specimens were then age-flattened at 850F for one-half hour to attain the 180 ksi minimum yield strength level in the circumferential direction. Unhydrogenated specimens were given the same age-flattening treatment for comparison. Smooth and notched (K_t=8), both axially and circumferentially oriented specimens were tested at room temperature. Only circumferential specimens were tested at -40 and 400F. Results from these tests are shown in Table II and in Figure 1. It may be seen that the results are in good agreement with those of similar tests conducted on cold-rolled and aged sheet stock. (See Table II). It is noted that all of the data points obtained from testing notched (K_t=8) flow-turned specimens do not fall within the scatter band for cold-rolled material. There are two reasons for this. First, testing of cold-rolled material was conducted only parallel to the rolling direction. Secondly, specimens taken from the flow-turned cylinder were slightly curved after the age flattening treatment and this affected the stress field at the base of the notch.

Bump-up tests (for which the stress level was increased 5 ksi every 5 hours) have been concluded on notched (K_t=8) specimens at 70 and 400F, and are presently being conducted on similar specimens at -40F (See Table III). Results to date have been in good agreement with notched (K_t=8) tensile behavior (Tables II and III).

B. Weld Development

Analysis of crack initiation and growth resulting from porosity in TIG welds is continuing.

Specimens with configurations such as shown in Figure 2 are subjected to cyclic testing by the method originally described in Technical Report No. WAL 766.2/1-3.

Specimens are initially loaded to the proof stress level of 80,000 psi for three cycles of three minutes each. Additional three minute cycles are conducted with successive increases of 5,000 psi until failure occurs. Specimens are inspected radiographically after each cycle to determine crack initiation and growth.

A porosity rating scheme has been devised and is being used for all cyclic specimens. The rating system indicates porosity size, density and distribution by measuring five parameters. The total number of pores in the four-inch gage length and in the worst one inch of the gage length are counted; the distances between the closest pores within and outside the worst one inch are measured; and the diameter of the largest pore is measured. Of the total of 62 specimens prepared and tested thus far, 60 have been tested to destruction. Both cyclic and standard tensile strain rate (0.005 inch/inch/minute) testing have been used.

The most recent TIG-welded cyclic specimens (numbers 60 to 62) have been prepared to simulate a single-pass weld technique using a 7-inch per minute travel speed. The specimens contained only very light porosity. (This single pass weld technique had been intended for use on full scale components as described in Technical Report No. WAL 766.2/1-7. However, recent experience in joining such components to fixtures for hydrostatic testing has disclosed difficulties with this practice.) For base line data, specimen Number 60 was tested at the standard tensile strain rate (0.005 inch/inch/minute) and failed at 170,000 psi with 9 per cent elongation. Failure occurred in the cold-rolled and aged parent material. Figure 3 shows the specimen after failure and indicates the direction of crack propagation and where yielding occurred.

Specimens numbers 61 and 62 have been cycled to 160,000 psi without failure or radiographic evidence of cracking. Testing is being continued.

Three additional cyclic specimens are being prepared from cold-rolled (50 per cent reduction) and aged (850F(1/2)AC + 800F(2)AC) sheet stock employing a V-type prepared joint and two-pass TIG-weld schedule similar to that recently adopted for joining full scale components. (See Section E, Full Scale Components). The smooth and notched (K_t=8) tensile and fracture toughness (G_c) properties as well as the bend ductility and microstructures of these welds will be investigated.

As reported previously in Technical Report No. WAL 766.2/1-8, bend specimens cut from girth welded cylinders prepared from 40-inch diameter hoops of rolled and welded sheet stock exhibited weld ductility superior to bend specimens prepared from flat weld panels even though similar weld schedules had been employed. The properties of this 40-inch diameter circumferential weld have been evaluated by smooth and notched (K_t=8) tensile tests (Table IV). These results demonstrate the excellent ductility and notched (K_t=8) strength of the weld. A comparison of the failed test specimens from the two subject welds is presented in Figure 4, clearly showing the greater elongation and reduction in area observed for the full scale circumferential weld. The fracture surfaces shown in Figure 5 indicate that the 40-inch diameter weld had a tendency to fail in a more ductile cup-cone manner while the flat test panel weld had a relatively brittle appearing flat and cleavage facetted fracture surface.

As reported in Technical Report No. WAL 766.2/1-8, no differences in microstructure or composition have been observed to account for this difference in ductility. The only difference noted has been that the full scale circumferential weld bead is wider than the flat test panel bead. This difference in geometry could result in ductility differences in transverse smooth tensile tests but not in edge notched tensile behavior (notches at weld centers). Additional microscopy, including electron microscopy, has failed to establish microstructural differences. Weld bead interstitial analyses are currently being rechecked.

Tensile properties have been determined for Ti-6Al-6V-2Sn alloy ring-rolled forgings at 70F. These forgings had been TIG-welded using AMS 4951 (commercially pure titanium) filler wire and were solution treated at 1630F (water quench), and subsequently aged at 1000 to 1100F. Test results are presented in Table V and indicate that no improvement in weld ductility was realized by solution treating prior to aging. To gain a further understanding of the behavior of this alloy, heat treatment response curves (Figures 6 and 7), have been determined for both weld metal and parent metal over a temperature range of 400 to 1500F.

This study shows that solution treated parent metal ages at temperatures as low as 400F. Heat treatments at temperatures in the range of 400 to 1100F were conducted in air. Heating at 1300F and above was accomplished in an argon atmosphere. As the aging temperatures and times are increased, hardness increases until it reaches the maximum value encountered in this investigation (RC48) after eight hours of aging at 700F. At 900F, overaging begins after about two hours, and at 1100F only the over-aged portion of the curve was observed. The weld metal behavior was considerably different since the initial as-welded hardness is high (RC41 to 42). Treatments at 500F did not affect the weld hardness. An 1100F aging treatment increased the hardness slightly to about RC43 to 44. At 1300F, a hardness increase was noted for the first hour after which the hardness decreased. Treatments at 1400 and 1500F annealed the weld metal to a hardness level of RC34 to 35. It appears from these results that the only true half age-weld-half age sequence must employ an aging temperature of 500F.

Tensile tests are therefore being conducted on parent metal aged from 1 to 4 hours at 500F and on material half aged (500F(1)AC), welded and half aged (500F(1)AC). It is presently intended that these tests will complete the weldability evaluation of the subject alloy under this program.

C. Forging Practice

1. Press Forging - Wyman-Gordon has press-forged an additional full scale 40-inch diameter rear dome (ELA-9) in three operations at 1800, 1800, and 1750F by the dogbone

technique. This dome was forged in the same manner as rear dome ELA-8 with the exception that modifications developed by Wyman-Gordon were employed in the forging sequence. The preform was coated prior to final forging to minimize heat losses during transfer from the furnace to the press. Motion pictures were taken of the pressure gages to accurately determine peak pressures and strain rates. The aging response of ELA-9 has been determined by both Wyman-Gordon and Pratt & Whitney Aircraft. Specimens were machined from the polar and skirt extremities after the part had been solution treated at 1450F for one-half hour and water quenched. Tensile results (See Tables XI and Figure 27) after aging for various times at 900F have shown that this part is not capable of achieving the desired properties of 4.0 per cent minimum elongation at the 180,000 psi yield strength level. The aging response is similar to that of full scale rear dome ELA-8. Both domes reached the 175,000 psi yield strength level with 3 per cent minimum elongation after aging at 900F for 24 hours. The low values for tensile elongation are believed due to exceptionally coarse aging constituents (Figure 28).

2. Ring Rolling - Tensile properties (70F) of the 40-inch diameter ring re-solution treated at 1800F are presented and discussed in Section D, Flow-Turning Development. The tensile properties of two 14-inch diameter and one 40-inch diameter flow turned cylinders which had also been re-solution treated at 1800F prior to flow-turning are also reported in Section D.

D. Flow-Turning Development

The last two 14-inch diameter roll-forged rings, Numbers 9 and 10, have been given the second and final flow-turn pass using the modified rollers. The cylinder membrane was flow-turned to a wall thickness approximating that required for full scale design. Contoured weld joints were included. Cylinder Number 10 was sectioned in the as-flow-turned condition and circumferential smooth and notched (K_t=8) tensile specimens were flattened during the stress relief cycle. Tensile results in both the axial and circumferential directions are shown in Table VI and in Figure 8. Cylinder Number 9 was sectioned after stress relieving at 850F for 30 minutes and smooth and notched (K_t=8) tensile properties in the axial direction are shown in Table VII and in Figure 9. The faster aging response exhibited by cylinder Number 9 is believed to be the result of the higher reduction during the second flow-turn pass. (Cylinder Number 9 received 48.2 per cent reduction and cylinder Number 10 received 42.5 per cent reduction.) The flow-turning parameters are shown in Table IX. Otherwise, the cylinders show identical tensile properties. Fracture toughness (G_c) specimens are currently being prepared for evaluation of these cylinders.

As reported in Technical Report No. WAL 766.2/1-8, subscale blanks numbers 7 and 8 showed erratic tensile behavior in the axial direction. It was further reported that the erratic behavior was caused by microcracks on the outside surface resulting from roller misalignment. To analyze the machine behavior during the flow-turning operation, pressure gages were installed in the hydraulic loading systems on both roller carriages. These gages indicated that the master carriage would consistently assume approximately 70 per cent of the flow-turning load although the rollers were accurately aligned under no-load conditions. A dial indicator was mounted on a support extending between both roller carriages and bridging the mandrel to measure roller misalignment under load conditions. (See Figure 10) The dial indicator showed that the slave roller would lag behind the master roller under feed loads. The amount of misalignment would vary with feed load with a maximum of .200 inch misalignment recorded under maximum feed loads. Using the bridged indicator to measure the relative position of the rollers, it is possible to advance the slave roller into alignment with the master roller during the flow-turning operation through the use of the machine controls provided. This method is especially helpful in maintaining roller alignment during contour flow-turning of weld joints when feed loads are changing. The effectiveness of this roller aligning method was indicated by the pressure gages which showed that the master carriage was assuming approximately 55 per cent of the load while the slave roller carriage was assuming the remainder of the load.

Alignment of the rollers was maintained by the use of the bridged indicator during the second pass flow-turning of subscale blanks numbers 9 and 10. As a result of the satisfactory performance on these two blanks, the bridged indicator was used to maintain roller alignment on all subsequent flow-turning operations.

The first two full scale roll-forged rings have been re-solution heat treated at 1800F, machined into flow-turn blanks, and given the first flow-turn pass. Because the carriage locks slipped during the first pass on the first blank, two passes were required to achieve the reduction intended for the first pass. No adverse effects were noted as a result of the light reductions. The final pass would have provided sufficient reduction to achieve the necessary cold working to promote aging to the required strength level. However, the weld development program required weld test hoops of flow-turned material. This first cylinder was, therefore, sectioned into hoops without being given the second flow-turn pass and was utilized for weld trials prior to welding case components to burst test adapters.

The second full scale blank was second pass flow-turned with satisfactory results. The flow-turn parameters are shown in Table IX. A 4-inch long test piece was flow-turned as part of the cylinder and after stress relieving was trimmed off. Figure 11 shows the complete cylinder, including the test piece, being set up for trimming. The test piece provided material for tests of tensile properties. The results of these tests are shown in Table VIII and in Figure 12.

The aging response of the second 40-inch diameter flow-turned cylinder indicated that this part is capable of attaining the 200,000 psi minimum yield strength level in the circumferential direction with 4 per cent minimum elongation. In the as-stress-relieved condition (850F (1/2) AC) this part has 180,000 psi minimum yield strength with 6 per cent elongation.

Based on the excellent tensile results from subscale cylinders numbers 9 and 10 and the second full scale cylinder, the remaining five full scale roll forged rings were re-solution-treated at 1800F for 15 minutes (water quenched) and machined into flow-turn blanks. Tensile results (70F) of specimens from the 40-inch roll forged rings after re-solution treatment showed that the reduction in area was increased to a range of 49 to 59 per cent (Table X) as anticipated. Reference Technical Report No. WAL 766.2/1-7. The first two full scale blanks and subscale blanks numbers 9 and 10 had been re-solution treated at 1800F for 15 minutes prior to flow-turning. In each case the material responded more favorably to the severe deformation process imposed by flow-turning. The results from tensile specimens which were re-solution treated with the ring forgings have shown the most significant improvement in tensile properties to be in reduction in area. Flow-turning experience within this program has qualitatively indicated that tensile reduction of area is the best measure of flow-turnability of B-120 VCA titanium alloy.

Full scale blanks numbers 3, 4, 5, and 6 were flow-turned first pass. The flow-turn parameters and blank dimensions are shown in Table IX.

As noted in Table IX, blank number 3 was reduced in diameter by .067-inch during the first pass. The decrease in diameter was caused by the higher flow-turn reduction resulting from less mandrel deflection with the rollers properly aligned. Subsequent blanks were flow-turned with the machine preset for the lower deflection and very little diametrical change was noted as a result of flow-turning.

Blanks numbers 3, 4, 5, and 6 were stress relieved at 850F for 30 minutes and a one-half inch test section was machined from one end of each blank to provide material both for evaluating annealing temperatures and for specimens to be annealed with the blanks. The four blanks were then annealed at 1500 to 1550F for 30 minutes and fan air cooled. They are now to be cleaned and inspected in preparation for the second and final pass.

E. Fabrication and Hydrostatic Testing of Full Scale Components

Rear dome ELA-6 was completely machined and welded to an adapter for component burst testing. The single pass TIG weld schedule (7 inches per minute travel speed) developed for full scale components on the rolled and axially welded 40-inch diameter sheet stock test rings was attempted on rear dome ELA-6 burst test assembly. The resultant weld contained excessive mismatch and several areas of incomplete weld penetration. Both of these characteristics have been attributed to differences in geometry between the rear dome and the mating adapter ring resulting in differential heat dissipation. The rear dome inside contour made it difficult to obtain satisfactory contact with the copper back-up fixture, and a relatively thin section in the dome near the weld joint permitted less heat dissipation than through the adapter ring. These conditions resulted in diametral growth of the dome relative to the adapter. To avoid the very extensive manual repair welding required, the weld was sectioned from the assembly and the weld joint remachined. The copper back-up fixture was reshaped to more ideally match the inside surface of the dome. More efficient outside clamping rings were designed and the assembly was then rewelded by a similar single pass technique. In spite of these improvements, considerable weld mismatch and areas of incomplete penetration again occurred.

An automatic inside TIG weld pass was performed with filler wire additions. Radiographic inspection indicated that substantially all areas of incomplete fusion had been eliminated. Those areas which remained were manually repair welded. Radiographic inspection after these repairs revealed no defects other than light to moderate weld porosity. After welding, bolt holes in the adapter flange and rear dome aft closure flange were machined.

Rear dome ELA-6 weldment was then instrumented with strain gages and assembled for burst testing (See Figure 13). The burst test schedule used was as follows. The hydraulic proof pressure of 575 psig at 70F was applied in increments of 150 psig. The component was then subjected to three cycles between 575 psig and ambient pressures. Following cycling the pressure was increased in 100 psig increments until burst occurred at 1184 psig. This burst pressure was significantly higher than the goal of 25 per cent above proof pressure, indicating an excellent burst margin for both the forged dome and the weld. All strain gage data was recorded at each increment until yielding exceeded strain gage limits.

Rear dome burst test component ELA-6 ruptured circumferentially with the failure origin at the weld-bead heat-affected zone interface of a manual repair weld (See Figures 14 to 16). Extensive yielding of the dome occurred prior to rupture, as may be noted in Figure 14.

Failure occurred at the inside surface with no indication of a prior defect (Figure 16). Fracture surfaces showed shear-type failures in both heavy and thin sections of the forged dome. Thin areas appeared ductile but heavy sections appeared less ductile with a tendency toward intergranular failure. (Figures 17 and 18). The fracture propagation showed a definite tendency to follow manual repair welds (Figure 19). Mechanical property evaluation of the dome and circumferential weld are now in process. An analysis of the strain gage data is also continuing.

To eliminate the difficulties encountered during welding of ELA-6, it was decided to develop a two-pass TIG-welding method which would reduce the instantaneous heat input during welding and thereby minimize relative growth of the components being welded. The new technique was developed on full scale test rings. Penetration was very uniform and only slight weld porosity resulted. This two-pass weld method appeared to give considerable improvement over the single-pass method previously used.

The two-pass method was used to fabricate the component burst test assemblies of front dome ELA-5 and the first flow-turned center section. These welds were acceptable by the radiographic standards employed for steel rocket motor cases (Technical Report No. 766.2/1-7) and required no repair welding.

Machining of front dome ELA-5 was completed. The rise-and-fall and skip-turning finish machining operations as described in Technical Report Number WAL 766.2/1-8 are shown in Figures 20and21. Front dome ELA-5 was then welded to a burst test adapter (See Figures 22and23) and bolt holes were machined in the polar port and in the adapter flange. The dome is currently being instrumented with strain gages in preparation for burst testing.

The second flow-turned cylinder was expanded approximately .200 inch to the desired diameter. The expanding operation was necessary because the mandrel upon which the cylinder was flow-turned is smaller than would be desired in view of the modified flow-turn practice which avoids diametral growth. The cylinder was welded to burst test adapters and instrumented with strain gages. The cylinder was then hydrostatically pressure tested to burst conforming to the same burst test schedule applied to rear dome ELA-6. The cylinder assembly burst prematurely at 540 psig hydraulic pressure. Failure initiated in the girth weld bead and propagated axially into the adjacent adapter and cylinder section (Figure 24). Preliminary examination of the girth weld fracture surface revealed that failure had apparently originated at a transverse prior crack through a porosity pore (Figure 25). Fracture surfaces in the flow-turned center section showed a ductile, 100 per cent shear failure (See Figure 26).

A detailed evaluation of this assembly is now being conducted in order to more fully establish the cause of failure and the component and weld properties.

F. Evaluation of Ti-15 Mo Alloy

Two 24 x 36 x 0.072-inch sheets of beta stabilized Ti-15 Mo alloy have been received for evaluation. One had been solution treated at 1508F and the other had been solution treated and aged (1508F + 977F(16)AC).

The results of chemical analysis are presented in Table XII. Bend and tensile properties have been determined at 70F both parallel and perpendicular to the mill rolling direction. These properties are tabulated in Tables XIII and XIV. Results to date indicate that this alloy has a lower strength but is more ductile than B-120 VCA Titanium alloy when compared in the solution treated conditions (1508F and 1450F respectively). The subject alloy exhibited a yield strength of 157,000 psi with 8.5 per cent elongation after aging at 977F for 16 hours (Table XIII). The notched (K_t=8) tensile strength in this condition was unexpectedly low (113,400 to 127,400 psi). Very little anisotropy was noted.

Bend tests on solution treated material confirmed the excellent ductility illustrated by tensile properties (Table XIV). The solution treated and aged sheet exhibited poor bend ductility and some anisotropy with the best ductility occurring parallel to the rolling direction. Typical microstructures of solution treated, and solution treated and aged material are shown in Figures 29 to 31. The solution treated material exhibited an equi-axed grain structure with evidence of banding or alloy segregation (Figure 29). The structure of solution treated and aged sheet also was equi-axed and showed a plate-like aging constituent emanating from grain boundaries and a non-resolvable matrix phase (Figures 30 and 31).

G. Conclusions

1. Tensile data (70F) for Ti-6Al-6V-2Sn alloy TIG welds made with AMS 4951 (commercially pure titanium) filler wire reveal that poor weld ductility results from solution treating (1630F) and aging (1000 to 1100F) after welding.

2. From test piece evaluation only (polar and rim extremities), the full scale press-forging technique using three operations at 1800, 1800, and 1750F developed for front and rear domes produces forgings with an inherent range of mechanical properties, with some having tensile property minimums as low as 175,000 psi yield strength in some areas and 3 per cent elongation in other areas. Performance of parts with these minimal properties is to be established by hydrostatic testing.

3. A full scale rear dome, press-forged by the above technique and aged to the 180,000 psi minimum yield strength level with a 4 per cent minimum elongation demonstrated excellent performance in hydrostatic testing. Before bursting, the dome sustained an internal pressure of 1184 psig which is 206 per cent of proof pressure.

4. The results of the subscale flow-turning program have shown that the flow turnability of B-120 VCA titanium roll-forged rings is improved after solution heat-treatment at 1800F for 15 minutes and a water quench. No adverse effects were observed in the aging response and aged properties of cylinders flow-turned from blanks heat treated in this fashion.

IV. PROGRAM PLANNED

The following program is planned at this time but is subject to revision as development progresses. Major emphasis has been directed toward the study of metallurgical factors influencing material behavior during forging flow-turning, heat treatment and welding, and also toward the resultant mechanical properties and performance capabilities. The results of these studies are now being utilized to achieve reliability in full scale components in the 175,000 to 200,000 psi yield strength range.

A. Effects of Interstitials

1. Hydrogen - Sustained-load testing of notched (K_t=8) specimens from the second subscale 14-inch diameter flow-turned cylinder (70 and 200 ppm hydrogen) now in process will complete the work intended under this phase of the program.

2. Oxygen - The remaining three of the nine originally intended pancake forgings will be upset at a later date if desired, but no further work is presently planned.

B. Forging Practice (Press Forging)

The mechanical properties achieved during this phase are currently being correlated with performance capabilities through hydrostatic burst testing of full scale press-forged components (front and rear domes). Front dome ELA-5 is being processed and will be burst tested. Rear dome ELA-8 will also be finish machined and hydrostatically tested. Results of these tests will assure performance capabilities of forgings to be incorporated into the full scale motor case.

C. Weld Development

Cyclic, as well as bend and tensile, tests will be continued to qualify the TIG-welding schedules to be employed for B-120 VCA titanium alloy full scale component and motor case fabrication.

A lower temperature (500F) age-weld-age sequence will be investigated for Ti-6Al-6V-2Sn alloy weldments. Tests after this sequence will complete the evaluation of this alloy.

D. Full Scale Components

1. Front Domes - Front dome assembly ELA-5 will be hydrostatically pressure tested to burst.

   Front dome ELA-7 will be rough machined and then held until results from the burst testing of front dome ELA-5 are available. If analysis indicates that the design of ELA-5 fulfilled the requirements then machining of ELA-7 will be completed.

2. Cylindrical Center Sections - An investigation will be carried out on the burst-tested cylindrical center section to determine the origin and type of failure along with an analysis of the strain data.

   Four of the machined forged rings are to be flow-turned into cylindrical center sections. One of these will be aged to a 200,000 psi yield strength level and burst tested as a component and another will be used in fabricating a complete motor case. The seventh blank is being held in the as-machined condition for future consideration.

3. Rear Domes - Rear dome ELA-1 will be machined for use in fabricating the full scale motor case and ELA-8 will be machined for component hydrostatic burst testing.

E. Evaluation of Ti-15 Mo Alloy

Future efforts in the investigation of this alloy will include parent material aging response in the solution-treated and cold-worked conditions and determination of TIG weldability.

APPENDIX A

Tables

TABLE I

Status of Component Development and
Laboratory Investigations

A. Laboratory Investigations

Program	Work Location	Type of Material	Status: Material	Status: Investigation
Effect of Interstitials (Hydrogen) on Notched Sensitivity Under Sustained Loads	PWA[1]	Sheet Stock and Flow-Turned Cylinders (14 and 40-Inch Diameter)	Received by PWA[2,3]	Sheet Stock and 40-Inch Diameter Cylinder Evaluations Completed. Evaluation of 14-Inch Diameter Flow-Turned Cylinder in Process
Effect of Interstitials (Oxygen) on Aging Response, Notch Sensitivity, and Stress Corrosion Susceptibility	Wyman-Gordon[4] (Forging) PWA (Evaluation)	Open Die Pancakes (9 pieces)	Received by Wyman-Gordon	Seven Pieces Forged and Evaluation Completed. No Further Work Anticipated at this Time
Metallographic (Electron Microscope, Diffraction and Microprobe Techniques)	Battelle Memorial Institute	Press-Forged, Flow-Turned and TIG and Electron Beam-Welded Material	No Material Being Evaluated at this Time	No Additional Work in Process at this Time
X-Ray Diffraction Studies of Flow-Turned Material	Manlabs[5]	Flow-Turned Material	No Material Being Evaluated at this Time	No Additional Work in Process at this Time
Weld Improvement	PWA	Sheet and Plate Stock	Received by PWA[3]	Investigation Continuing
Effect of Press-Forging (High and Low Strain Rates) on Aging Response and Aged Tensile Ductility	Wyman-Gordon (Forging) and PWA (Evaluation)	Open Die Pancakes		

B. Subscale Components

Program	Work Location	Component	No. of Pieces Allocated	Status: Material	Status: Fabrication
Effect of Press-Forging (High and Low Strain Rates) on Aging Response and Aged Tensile Ductility	Wyman-Gordon (Forging) and PWA (Evaluation)	Open Die Pancakes	8	Received by Wyman-Gordon	Seven Pieces Forged and Evaluated, Final Piece will not be Forged at this Time.
Press-Forging (dogbone technique)	Wyman-Gordon (Forging) and PWA (Evaluation)	14-Inch Diameter Domes	3	Received by Wyman-Gordon	Three Pieces Forged and Evaluated. No Further Work Intended at this Time
Press-Forging (Pancake and Preform Technique)	Wyman-Gordon (Forging) and PWA (Evaluation)	14-Inch Diameter Domes	6	Received by Wyman-Gordon	Six Pieces Forged and Evaluated. No Further Work Intended at this Time.
Hammer Forging	Ladish[6] (Forging) and PWA (Evaluation)	Closed-Die Pancakes with Offset Bosses	4	Received by Ladish	Four Pieces Forged and Evaluated. No Further Work Intended at this Time.
Ring Rolling	Ladish (Rolling) and PWA (Evaluation)	14-Inch Diameter Rings	6	Received by Ladish	Six Pieces Rolled and Evaluated. No Further Work Intended at this Time.
Flow-Turning	PWA	9.4 and 14-Inch Diameter Rings and Blanks		1) Two 9.4-Inch Diameter Rolled Rings 2) Nine 9.4-Inch Diameter Rolled and Welded Blanks 3) Three 14-Inch Diameter Rolled and Welded Blanks 4) Twelve 14-Inch Diameter Rolled Rings	1) Two 9.4-Inch Dia[illegible] Flow-Turned and [illegible] 2) All 9.4-Inch and [illegible] Diameter Rolled [illegible] Flow-Turned and [illegible] Further Work on [illegible] Welded Blanks In[illegible] Time. 3) Ten 14-Inch Diameter Rolled Rings Flow-Turned and Evaluated. Two Rings Diverted to Hydrogen

Hammer Forging	Ladish (Forging) and PWA (Evaluation)	Pancakes with Offset Bosses			Evaluated. No Further Work Intended at this Time.
Ring Rolling	Ladish (Rolling) and PWA (Evaluation)	14-Inch Diameter Rings	6	Received by Ladish	Six Pieces Rolled and Evaluated. No Further Work Intended at this Time.
Flow-Turning	PWA	9.4 and 14-Inch Diameter Rings and Blanks		1) Two 9.4-Inch Diameter Rolled Rings 2) Nine 9.4-Inch Diameter Rolled and Welded Blanks 3) Three 14-Inch Diameter Rolled and Welded Blanks 4) Twelve 14-Inch Diameter Rolled Rings	1) Two 9.4-Inch Diameter Rings Flow-Turned and Evaluated. 2) All 9.4-Inch and 14-Inch Diameter Rolled and Welded Blanks Flow-Turned and Evaluated. No Further Work on Rolled and Welded Blanks Intended at this Time. 3) Ten 14-Inch Diameter Rolled Rings Flow-Turned and Evaluated. Two Rings Diverted to Hydrogen Investigation Phase.
C. Full Scale Components					
Press Forging (Pancake and Preform Technique)	Wyman-Gordon (Forging) and PWA (Evaluation)	40-Inch Diameter Front Domes	6	Received by Wyman-Gordon	First Piece Forged in Steel Pershing Dies (1900F) and Evaluated. Two Additional Pieces Forged at 1850F in OMRO Dies and Evaluated. One Piece Forged at 1750F in OMRO Dies, Evaluated and Being Machined into Burst Test Component. Final Two Pieces Forged in OMRO Dies at 1750F, Evaluated, and Aged. One Piece Being Machined into Component for Case.
Press-Forging (Dogbone Technique)	Wyman-Gordon (Forging) and PWA (Evaluation)	40-Inch Diameter Rear Domes	5	Received by Wyman-Gordon	Two Pieces Forged in OMRO Dies at 1850F and 1800F and Evaluated. Piece Forged at 1800F Was Aged and Is Being Machined into Component for Case. One Piece Forged at 1750F, Evaluated, Machined into Burst Test Component and Hydrostatically Tested. Two Additional Pieces Forged at 1750F, Evaluated, and Aged. One Piece Is Being Machined into Burst Test Component.
Ring Rolling	Ladish (Rolling) and PWA (Evaluation)	40-Inch Diameter Rolled Rings	7	Received by Ladish	All Seven Pieces Rolled at 1900F, Received and Evaluated after 1450F Solution Treatment. Pieces Were Re-solution Treated at 1800F and Re-evaluated.
Flow-Turning	PWA	40-Inch Diameter Cylinders	9	Received by PWA	Two Pieces Flow-Turned and Evaluated. One Piece Was Burst Tested. Four Additional Pieces Were Flow-Turned First Pass. One Piece Held in Reserve.

(1) Pratt & Whitney Aircraft Division, East Hartford, Connecticut
(2) Two 40-Inch Diameter Rings Transferred from Thiokol (7) Contract RM-962
(3) 0.125, 0.250 and 0.375-Inch Thick Sheet and Plate Stock Transferred from Thiokol Contract RM-962
(4) Wyman-Gordon Co., Grafton, Mass.
(5) Manlabs, Inc., Cambridge, Mass.
(6) Ladish Co, Milwaukee, Wis.
(7) Thiokol Chemical Corporation, Huntsville, Ala.

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TABLE II

Smooth and Notched (K_t=8) Tensile Properties of Flow-Turned (50% Reduction) and Aged (850F (1/2) AC) 14-Inch Diameter Cylinder with Hydrogen Contents of 70 and 200 ppm

Specimen Direction	Hydrogen Content (ppm)	Test Temp °F	T. S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 in) (per cent)	Notched Tensile Strength (K_t=8) (ksi)
Axial	70	70	189.3	184.8	5.0	181.0
Axial	70	70	189.1	---	4.5	170.6
Axial	200	70	186.3	173.1	5.0	180.0
Axial	200	70	189.5	186.0	4.0	156.5
Circ.	70	70	195.6	183.5	7.0	141.8
Circ.	70	70	195.1	185.6	6.5	151.0
Circ.	200	70	192.5	186.4	6.5	170.2
Circ.	200	70	194.5	186.5	7.0	157.0
Circ.	70	-40	215.0	199.0	5.0	165.0
Circ.	70	-40	216.0	202.0	5.0	162.0
Circ.	200	-40	216.5	200.0	5.0	165.6
Circ.	200	-40	208.0	194.0	2.0	168.5
Circ.	70	400	184.5	170.5	5.0	170.0
Circ.	70	400	183.5	169.0	5.0	159.8
Circ.	200	400	187.0	170.0	7.0	173.5
Circ.	200	400	185.5	170.0	4.0	160.0

TABLE III

Results of Bump-Up Sustained Load Tensile Tests (5 ksi Stress Increase Every 5 Hours) Conducted on Axial and Circumferential Notched (K_t=8) Specimens From Flow-Turned (50% Reduction) and Aged (850F(1/2)AC) 14-Inch Diameter Cylinder

Direction	Test Temp. (°F)	Hydrogen Content (ppm)	Initial Load Stress (ksi)	Failure Stress (ksi)	Remarks
Axial	70	70	145	170	1 min at 170 ksi
Axial	70	200	145	160	Ruptured on increasing load to 165 ksi
Circ.	70	70	130	130	Failed on loading
Circ.	70	200	130	145	Failed after 0.1 hour
Circ.	400	70	150	165	Failed after 1.0 min.
Circ.	400	200	150	150	Failed after 1.0 min.

TABLE IV

Transverse Tensile Properties (70F) of Single Pass TIG Welds made on a 40-Inch Diameter Test Ring (Rolled and Welded 0.140 Inch Thick Sheet Stock) and on a Flat Test Panel using a 7-Inch Per Minute Travel Speed

Weld Bead	T.S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 inch) (per cent)	Notched Tensile* Strength (K_t=8) (ksi)
I. 40-Inch Diameter Test Ring (0.107 per cent oxygen, 100 ppm hydrogen)				
Intact	147.8	137.3	12.0	170.8
Intact	143.6	131.8	12.0	170.3
Ground Flush	130.3	123.8	10.0	156.3
Ground Flush	131.5	124.0	12.0	147.0
II. Test Panels (0.117 per cent oxygen and 140 ppm hydrogen)				
Intact	141.0	129.3	8.5	107.4
Intact	138.8	126.3	12.0	109.3
Ground Flush	127.6	121.0	7.5	
Ground Flush	124.5	120.3	7.0	

*External notches at weld centers

TABLE V

Transverse Tensile Properties (70F) of Ti-6Al-6V-2Sn Alloy Rolled Ring Forging Welded with AMS 4951 (Commercially Pure Titanium) Solution Treated at 1630F for One-Half Hour (Water Quench) and Aged at 1000 to 1100F

Condition	Weld Bead	T.S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 in) (per cent)	Failure* Location
1000F (4) AC	Intact	194.2	193.0	1.0	HAZ
1000F (4) AC	Intact	199.5	186.5	1.0	HAZ
1000F (4) AC	Flush	189.5	186.8	1.0	WM
1000F (4) AC	Flush	185.5	182.5	1.0	HAZ
1000F (8) AC	Intact	196.0	193.0	1.0	HAZ
1000F (8) AC	Intact	192.8	189.0	1.0	HAZ
1000F (8) AC	Flush	184.2	181.2	1.0	WM
1050F (4) AC	Intact	174.4	---	1.0	WM
1050F (4) AC	Intact	195.6	183.5	1.5	PM
1050F (4) AC	Flush	175.0	168.6	1.0	WM
1050F (4) AC	Flush	178.0	174.0	1.0	WM
1050F (8) AC	Intact	187.6	185.4	1.0	WM
1050F (8) AC	Intact	195.5	185.0	2.0	WM
1050F (8) AC	Flush	167.0	---	1.0	HAZ
1050F (8) AC	Flush	175.5	167.2	1.5	WM
1100F (1) AC	Intact	192.4	181.2	5.0	PM
1100F (1) AC	Intact	192.5	180.0	2.0	HAZ
1100F (1) AC	Flush	182.0	172.0	1.0	HAZ
1100F (1) AC	Flush	181.2	172.5	1.0	WM
1100F (8) AC	Intact	178.4	178.4	1.0	HAZ
1100F (8) AC	Intact	187.8	176.0	1.0	HAZ
1100F (8) AC	Flush	167.4	162.0	2.0	HAZ
1100F (8) AC	Flush	171.6	164.4	2.0	HAZ

Welding Parameters - Single Pass, Square Butt Joint

1. Amperage - 163
2. Arc Voltage - 13
3. Travel Speed - 4.5 in/min
4. Filler Wire Diameter - 3/64 in.
5. Filler Wire Feed - 26 in/min
6. Gas Flow
   Helium to Torch - 40 cfh
   Helium to Trailer Cup - 45 cfh
   Argon to Backup Fixturing - 20 cfh

*WM - Weld Metal
HAZ - Heat affected zone
PM - Parent metal

TABLE VI

Tensile Properties (70F) of 14-Inch Diameter Cylinder Number 10 Flow-Turned by the Present Two-Pass Technique (50 Per Cent Reduction Per Pass), Stress-Relieved at 850F for One-Half Hour and Aged at 800F

Condition	Specimen Direction	T.S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 in) (per cent)	Notched Tensile Strength (K_t=8) (ksi)
As-stress-relieved	Axial	179.9	172.7	9.0	
As-stress-relieved	Axial	180.5	173.0	7.5	
As-stress-relieved	Circ.	188.3	175.6	9.0	
800F(1/2)AC	Axial	185.8	178.3	8.0	
800F(1/2)AC	Axial	186.2	175.5	7.0	
800F(1/2)AC	Circ.	194.0	182.8	7.0	
800F(1/2)AC	Circ.	195.3	184.0	7.0	
800F(1)AC	Axial	188.0	178.6	7.0	151.5
800F(1)AC	Axial	188.8	180.7	7.0	160.0
800F(1)AC	Circ.	204.5	192.3	6.0	169.0
800F(1)AC	Circ.	199.0	186.0	6.0	171.0
800F(2)AC	Axial	195.6	187.9	7.0	
800F(2)AC	Axial	198.7	189.5	6.0	
800F(2)AC	Circ.	206.0	190.5	6.0	
800F(2)AC	Circ.	205.0	191.4	6.0	
800F(4)AC	Axial	208.0	197.8	5.0	128.5
800F(4)AC	Axial	206.2	196.5	5.0	127.6
800F(4)AC	Circ.	217.5	207.0	5.0	146.8
800F(4)AC	Circ.	217.0	203.0	4.5	138.5
800F(8)AC	Circ.	227.0	216.0	3.0	121.0
800F(8)AC	Circ.	228.0	216.0	3.0	119.5
800F(8)AC	Axial				120.0
800F(8)AC	Axial				115.5

TABLE VII

Axial Tensile Properties (70F) of Subscale 14-Inch Diameter Cylinder Number 9 Flow-Turned by the Present Two-Pass Technique (50 Per Cent Reduction Per Pass), Stress-Relieved at 850F for One-Half Hour and Aged at 800F

Condition	T.S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 in) (per cent)	Notched Tensile Strength (K_t=8) (ksi)
As-stress-relieved	193.0	186.4	4.5	153.5
As-stress-relieved	200.2	191.0	5.0	147.5
800F(1/2)AC	205.0	193.6	5.0	
800F(1/2)AC	206.5	198.0	5.0	
800F(1)AC	208.5	196.5	5.0	138.0
800F(1)AC	215.5	204.5	3.0	149.6
800F(2)AC	218.0	209.0	5.0	
800F(2)AC	216.0	206.0	3.0	
800F(4)AC	231.5	210.0	3.0	
800F(4)AC	226.5	215.0	4.0	
800F(3)AC				128.4
800F(3)AC				137.8

TABLE VIII

Tensile Properties (70F) of Full Scale 40-Inch Diameter Ring Re-Solution Treated at 1800F Prior to Flow-Turning by the Present Two-Pass (50 Per Cent Reduction Per Pass) Technique, Stress-Relieved at 850F for One-Half Hour and Aged 800F

Condition	Direction	Specimen Gage Length (inch)	T.S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 in) (per cent)
As-stress-relieved	Axial	0.75	187.0	183.0	8.0
As-stress-relieved	Axial	0.75	183.8	179.5	7.3
As-stress-relieved	Circ.	1.0	198.5	186.0	6.0
As-stress-relieved	Circ.	1.0	197.5	185.5	6.5
As-stress-relieved	Circ.	0.75	199.5	187.0	4.0
As-stress-relieved	Circ.	0.75	200.0	190.8	4.7
800F (1/2) AC	Axial	0.75	196.0	187.5	6.7
800F (1/2) AC	Axial	0.75	196.5	188.0	7.3
800F (1/2) AC	Circ.	1.0	207.0	197.0	6.0
800F (1/2) AC	Circ.	1.0	206.5	197.2	5.0
800F (1) AC	Axial	0.75	199.0	188.5	4.0
800F (1) AC	Axial	0.75	199.0	190.0	6.7
800F (1) AC	Circ.	1.0	208.0	198.0	4.0
800F (1) AC	Circ.	1.0	209.0	198.0	4.5
800F (2) AC	Axial	0.75	204.5	195.8	5.3
800F (2) AC	Axial	0.75	204.0	196.0	5.3
800F (2) AC	Circ.	1.0	214.5	203.5	3.0
800F (2) AC	Circ.	1.0	215.0	194.7	3.5
800F (4) AC	Axial	0.75	214.0	204.5	4.0
800F (4) AC	Axial	0.75	207.0	196.0	3.3
800F (4) AC	Circ.	1.0	228.0	216.0	3.0
800F (4) AC	Circ.	1.0	231.5	220.0	4.0

TABLE IX

Flow-Turning Parameters and Dimensions of Flow-Turned Cylinders

Cylinder No.	Inside Diameter Before Flow-Turning (inches)	Wall Thickness Before Flow-Turning (inch)	Mandrel Speed (RPM)	Roller Feed (inches/min/roller)	Roller Tip Radius (inch)	Reduction (per cent)	Wall Thickness After Flow-Turning (inches)	Inside Diameter after Flow-Turning (inches)
First Flow-Turn Pass								
3	39.622	.302	52.5	1.05	.062	53.5	.140	39.555
4	39.623	.301	52.5	1.05	.062	45.7	.163	39.648
5	39.621	.300	52.5	1.05	.062	49.3	.152	39.616
6	39.625	.300	52.5	1.05	.062	48.0	.156	39.646
Second Flow-Turn Pass								
9	14.127	.130	150	3.0	.062 Modified	48.2	.067	14.130
10	14.128	.134	150	3.0	.062 Modified	42.5	.077	14.147
2	39.622	.153	55	1.0	.062 Modified	53.3	.072	39.645

TABLE X

Tensile Properties (70F) of 40-Inch Diameter Roll-Forged Rings Re-Solution Treated at 1800F for Fifteen Minutes and Water Quenched

Ring No.	T.S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 in) (per cent)	Reduction (per cent)	Notched Tensile Strength (K_t=8) (ksi)
2	134.8	125.7	25	59	211.0
2	138.3	126.9	20	54	212.0
3	137.2	126.5	19.5	50.5	209.0
3	138.0	127.3	21.5	49	217.2
6	136.3	---	21.5	49	211.5
6	136.3	127.0	24.0	59	218.8
7	136.5	125.6	20	57.5	216.0
7	146.3	---	18.5	57.5	216.0
8	139.0	---	21.0	59.5	216.0
8	143.5	129.5	18.5	51.0	211.5

TABLE XI

Tensile Properties (70F) of Full Scale 40-Inch Diameter Rear Dome ELA-9 Forged in Three Operations at 1800, 1800 and 1750F by the Dogbone Technique, Solution Treated at 1450F for One-Half Hour and Aged at 900F

Condition	Location	Direction	T.S. (ksi)	Y.S.(0.2%) (ksi)	Elong. (1 in) (per cent)	Reduction (per cent)
900F(12)AC	Pole	Tang.	178.0*	164.4	5.0	11.7
900F(12)AC	Pole	Tang.	178.7*	165.0	6.0	11.7
900F(12)AC	Pole	Radial	177.4*	163.2	7.5	16.8
900F(12)AC	Pole	Radial	180.1*	164.8	10.0	14.7
900F(12)AC	Skirt	Tang.	185.0*	172.9	4.0	8.6
900F(12)AC	Skirt	Tang.	185.0*	173.6	4.0	8.6
900F(18)AC	Pole	Tang.	184.2	168.0	7.0	9.0
900F(18)AC	Pole	Tang.	185.0	168.4	6.0	7.0
900F(18)AC	Pole	Radial	186.6	169.0	10.0	10.0
900F(18)AC	Pole	Radial	186.6	167.4	10.0	11.5
900F(18)AC	Skirt	Tang.	192.0	178.6	3.0	3.5
900F(18)AC	Skirt	Tang.	190.0	178.4	3.0	5.5
900F(20)AC	Pole	Tang.	184.6*	169.1	5.0	10.9
900F(20)AC	Pole	Tang.	188.7*	171.9	5.0	10.1
900F(20)AC	Pole	Radial	190.3*	173.4	9.0	13.9
900F(20)AC	Pole	Radial	187.8*	171.3	9.0	13.9
900F(20)AC	Skirt	Tang.	198.0*	185.2	3.0	6.2
900F(24)AC	Pole	Tang.	193.6	177.5	5.0	8.5
900F(24)AC	Pole	Tang.	194.2	177.8	5.0	6.0
900F(24)AC	Pole	Radial	193.6	173.8	8.0	12.0
900F(24)AC	Pole	Radial	193.6	177.5	7.0	10.5
900F(24)AC	Skirt	Tang.	197.5	187.2	3.0	4.0
900F(24)AC	Skirt	Tang.	199.0	186.6	3.5	5.0
900F(30)AC	Pole	Tang.	200.1*	186.4	5.0	7.0
900F(30)AC	Pole	Tang.	200.5*	186.2	4.0	6.2
900F(30)AC	Skirt	Tang.	200.7*	192.7	2.0	7.7
900F(30)AC	Skirt	Tang.	201.3*	193.1	2.5	5.1
1550 (1/2) WQ + 900F(241)AC	Pole	Tang.	175.6	160.8	5.0	8.0
1550 (1/2) WQ + 900F(241)AC	Pole	Tang.	177.8	164.0	5.5	8.0
1550 (1/2) WQ + 900F(241)AC	Pole	Radial	179.3	163.7	7.0	7.0
1550 (1/2) WQ + 900F(241)AC	Pole	Radial	182.0	166.0	6.5	10.0
1550 (1/2) WQ + 900F(241)AC	Skirt	Tang.	201.5	188.8	4.0	7.0
1550 (1/2) WQ + 900F(241)AC	Skirt	Tang.	198.8	186.7	3.5	4.0

TABLE XI (Continued)

Condition	Location	Direction	T.S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 in) (per cent)	Reduction (per cent)
1800F(1/4)WQ+ 900F(24)AC	Pole	Tang.	193.5	176.8	6.0	7.0
1800F(1/4)WQ+ 900F(24)AC	Pole	Tang.	193.8	177.0	6.0	5.0
1800F(1/4)WQ+ 900F(24)AC	Pole	Radial	174.0	171.0	2.0	2.0
1800F(1/4)WQ+ 900F(24)AC	Pole	Radial	173.3	171.6	2.0	0.5
1800F(1/4)WQ+ 900F(24)AC	Skirt	Tang.	175.3	173.7	2.5	1.0
1800F(1/4)WQ+ 900F(24)AC	Skirt	Tang.	170.9	---	2.5	1.0
1400F(2)WQ + 900F(12)AC	Pole	Tang.	152.3*	141.1	7.0	17.5
1400F(2)WQ + 900F(12)AC	Pole	Tang.	150.5*	139.5	9.0	15.1
1400F(2)WQ + 900F(12)AC	Skirt	Tang.	178.5*	165.4	5.0	10.1
1400F(2)WQ + 900F(12)AC	Skirt	Tang.	178.1*	165.8	5.0	8.6

* Data obtained by Wyman-Gordon

TABLE XII

Compositions of Ti-15 Mo Alloy Sheet Stock
(As-Recieved)

Sheet	Mo	Fe	O	H	N	C	Ti
Piece A, Solution Treated	15.36	<0.5	0.117	0.003	0.015	0.02	Bal.
Piece B, Solution Treated and Aged	14.70	<0.5	0.122	0.003	0.010	0.02	Bal.

TABLE XIII

Tensile Properties (70F) of Ti-15 Mo Alloy (0.072-Inch Gage) in the Solution Treated (1508F (1/2) WQ) and Solution Treated and Aged Conditions (1508F (1/2) WQ + 977(16)AC)

Orientation to Rolling Direction	Condition	T.S. (ksi)	Y.S. (0.2%) (ksi)	Elong. (1 in) (per cent)	Notched Tensile Strength (K_t=8) (ksi)
Parallel	1508F(1/2)WQ	114.6	101.0	22.0	128.0
Parallel	1508F(1/2)WQ	112.2	96.7	25.5	128.5
Transverse	1508F(1/2)WQ	110.5	91.8	24.0	132.0
Transverse	1508F(1/2)WQ	110.6	93.4	25.0	123.5
Parallel	1508F(1/2)WQ+977F(16)AC	171.2	156.5	9.0	116.6
Parallel	1508F(1/2)WQ+977F(16)AC	171.0	154.0	8.0	113.4
Transverse	1508F(1/2)WQ+977F(16)AC	174.0	159.0	8.5	122.4
Transverse	1508F(1/2)WQ+977F(16)AC	174.0	158.0	9.0	127.4

TABLE XIV

Bend Test (70F) Results on Ti-15 Mo Alloy in the Solution Treated, Solution Treated and Aged, and Solution Treated, Aged, and Subsequently Welded Conditions

Condition	Orientation to Rolling Direction	Bend* Diameter	Bend Angle (degrees)	Remarks
1508F(1/2)WQ	Parallel	1.0	152	Intact
1508F(1/2)WQ	Parallel	1.0	155	Intact
1508F(1/2)WQ	Transverse	1.0	148	Intact
1508F(1/2)WQ	Transverse	1.0	155	Intact
1508F(1/2)WQ+977F(16)AC	Parallel	7.4	40	Fracture
1508F(1/2)WQ+977F(16)AC	Parallel	7.8	27	Fracture
1508F(1/2)WQ+977F(16)AC	Parallel	9.0	88	Fracture
1508F(1/2)WQ+977F(16)AC	Parallel	9.0	87	Fracture
1508F(1/2)WQ+977F(16)AC	Transverse	9.0	45	Fracture
1508F(1/2)WQ+977F(16)AC	Transverse	9.7	42	Fracture
1508F(1/2)WQ+977F(16)AC	Transverse	11.7	33	Fracture
1508F(1/2)WQ+977F(16)AC	Transverse	15.6	117	Intact

*Ratio of mandrel diameter to specimen thickness

APPENDIX B

Figures

SMOOTH AND NOTCHED (Kt =8) TENSILE PROPERTIES VS. TEST TEMPERATURE FOR FLOW-TURNED, (50% REDUCTION) TO 0.070 - IN THICKNESS), AND AGED 14- INCH DIAMETER CYLINDER WITH HYDROGEN CONTENTS OF 70 AND 200 PPM

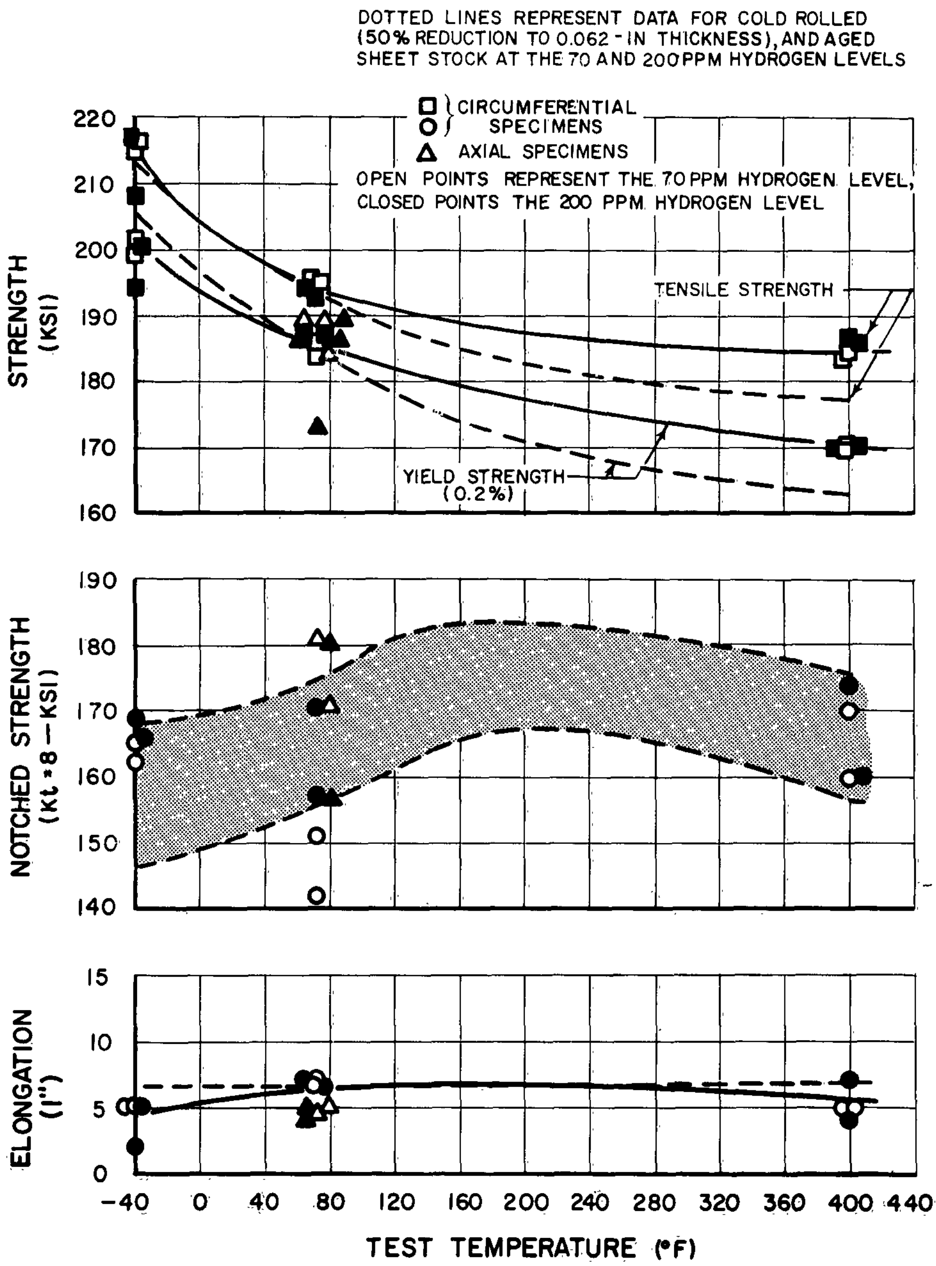


Figure 1

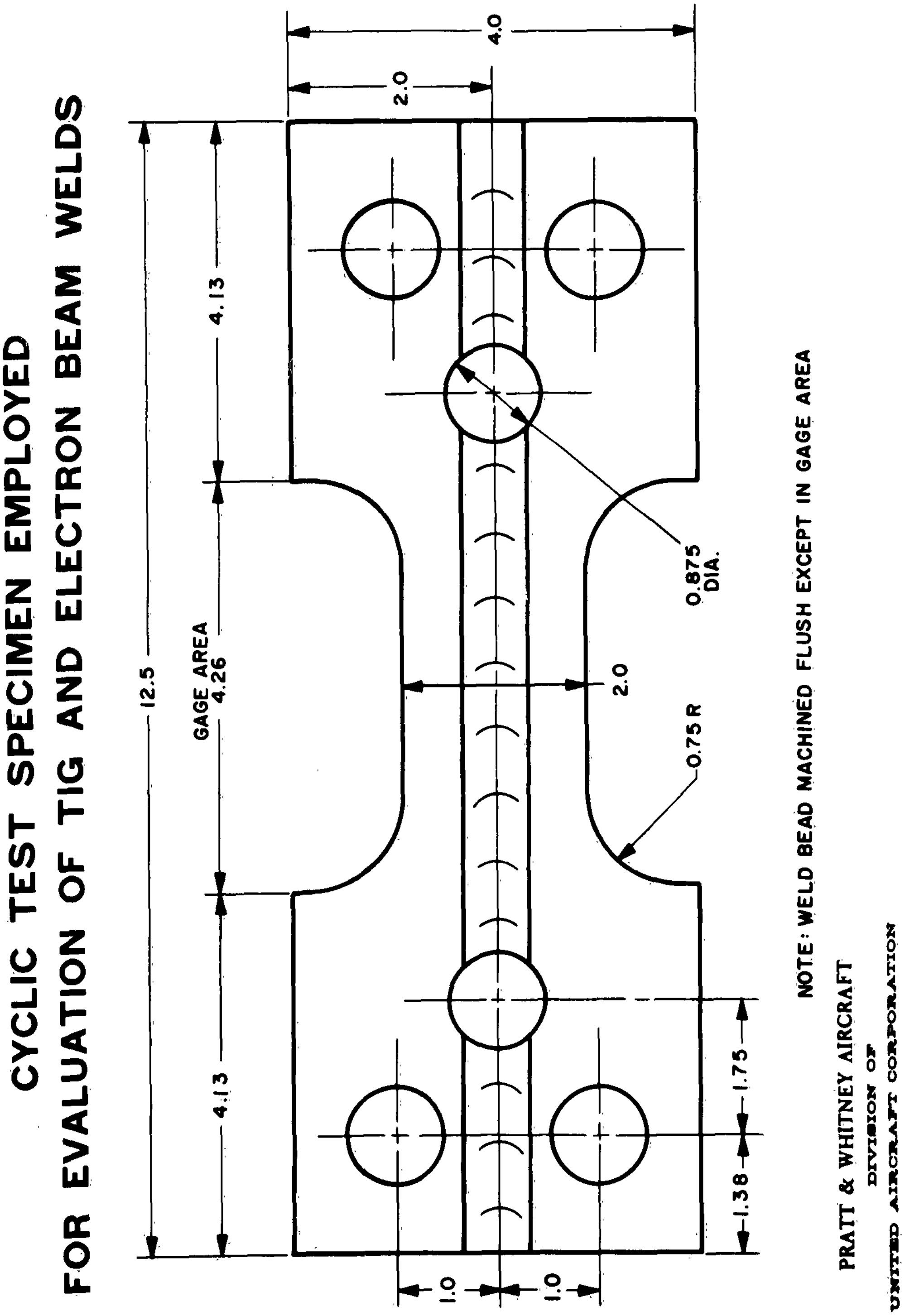
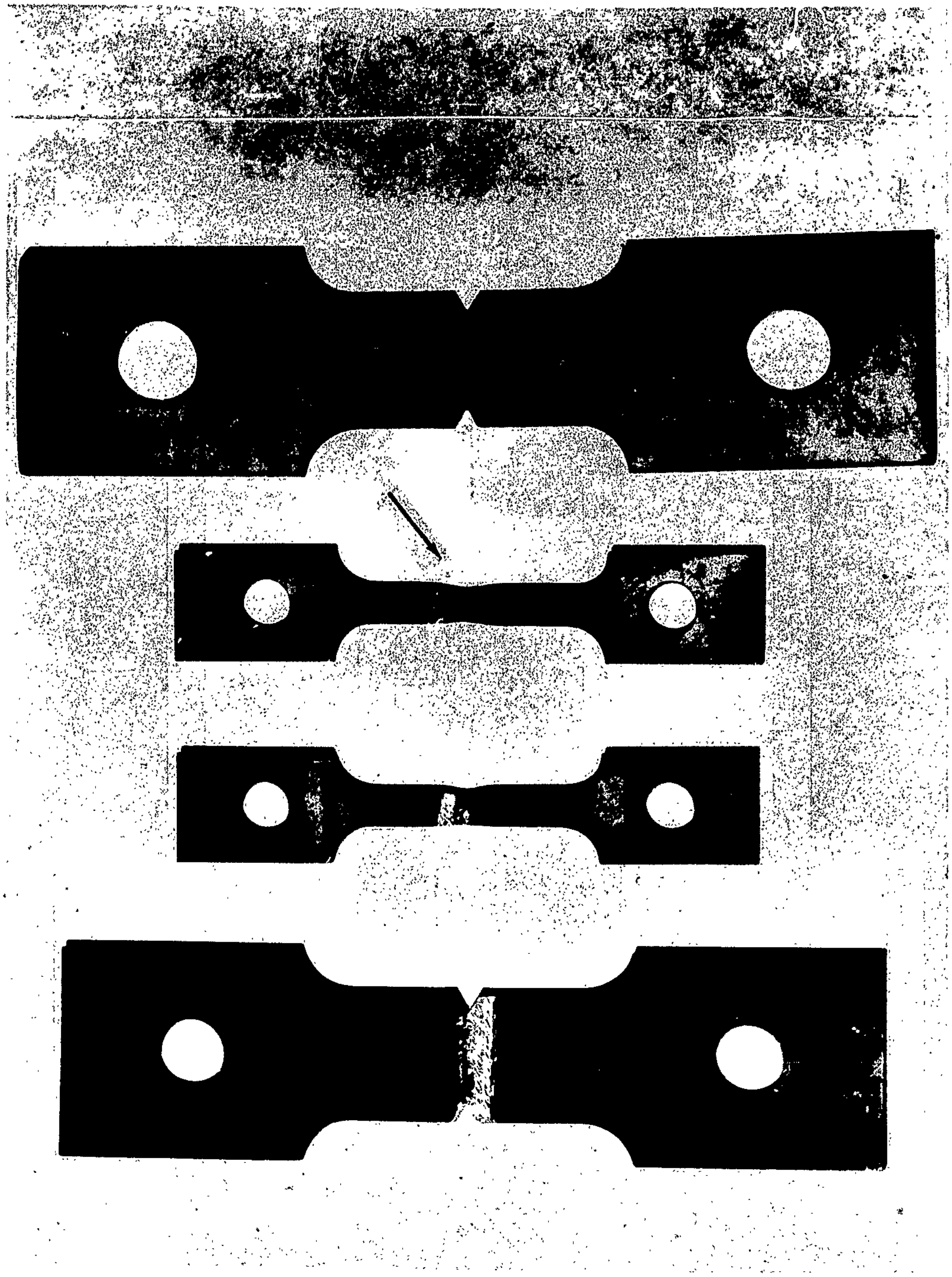

CYCLIC TEST SPECIMEN EMPLOYED
FOR EVALUATION OF TIG AND ELECTRON BEAM WELDS
4.0
2.0
12.5
4.13
GAGE AREA
4.26
4.13
0.875
DIA.
2.0
0.75 R
1.75
1.38
1.0
1.0
NOTE: WELD BEAD MACHINED FLUSH EXCEPT IN GAGE AREA
PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 2

MAG: 5X

SURFACE OF FAILED CYCLIC TEST SPECIMEN NUMBER 60 (170 KSI, 9 PER CENT ELONGATION). ARROWS INDICATE DIRECTION OF CRACK PROPAGATION. NOTE YIELDING ALONG FAILURE IN PARENT METAL, HEAT AFFECTED ZONE, AND WELD METAL

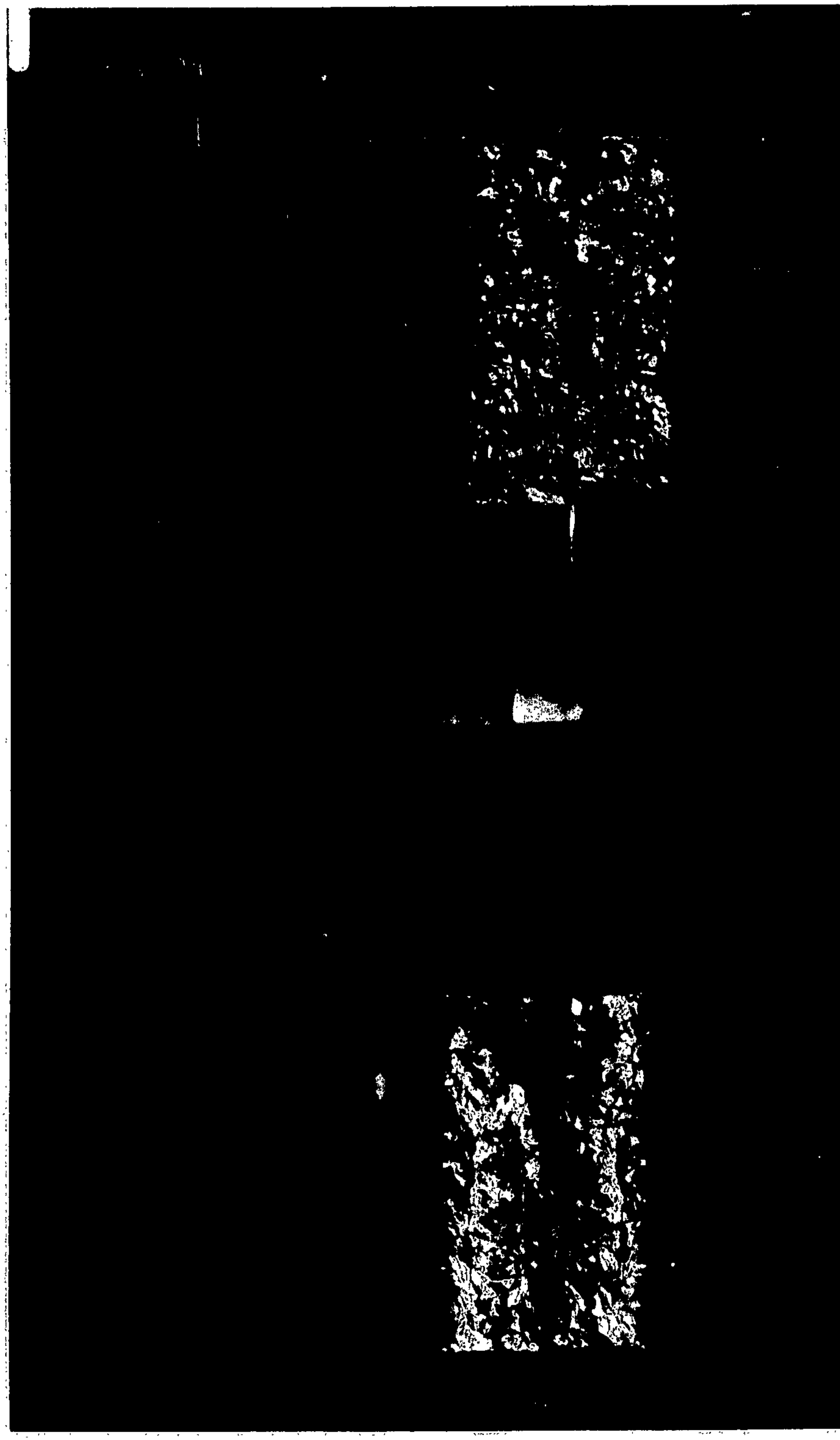
Figure 3



MAG: 0.9X

FAILED TENSILE SPECIMENS FROM FLAT WELD TEST PANELS (LEFT) AND 40-INCH DIAMETER WELD RING (RIGHT). NOTE THE GREATER ELONGATION AND REDUCTION IN AREA EXHIBITED BY THE SMOOTH SPECIMEN FROM THE 40-INCH DIAMETER RING (ARROW)

Figure 4



MAG: 4.5X

TYPICAL FRACTURE SURFACES OF NOTCHED (K_T=8) TENSILE SPECIMENS TAKEN FROM FLAT WELD TEST PANEL (RIGHT) AND 40-INCH DIAMETER WELD RING (LEFT). NOTE THE RELATIVELY DUCTILE CUP-CONE TYPE FAILURE OF THE SPECIMEN FROM 40-INCH DIAMETER RING AND THE BRITTLE CLEAVAGE APPEARANCE OF THE SPECIMEN FROM THE FLAT WELD TEST PANEL

Figure 5

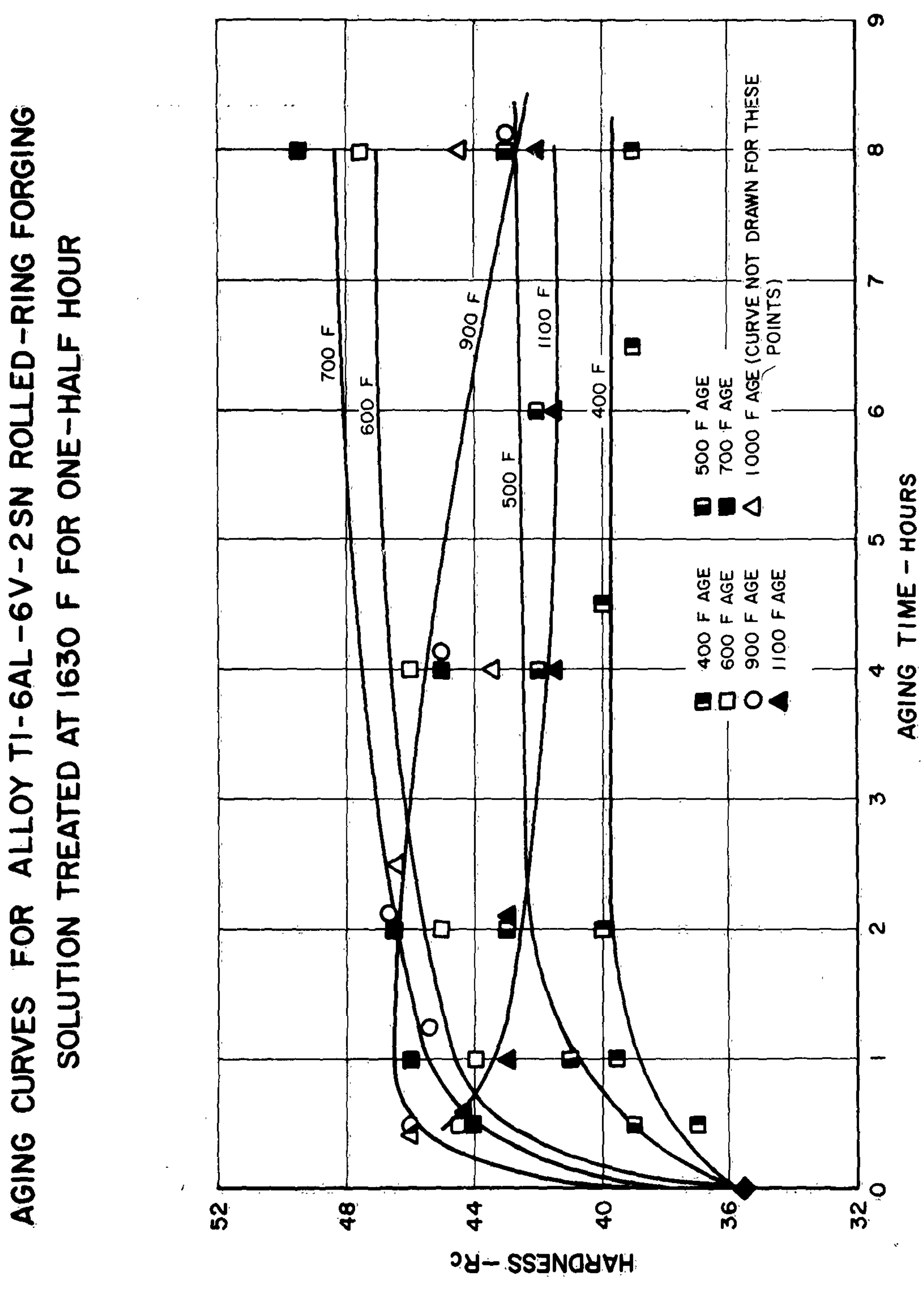

AGING CURVES FOR ALLOY TI-6AL-6V-2SN ROLLED-RING FORGING
SOLUTION TREATED AT 1630 F FOR ONE-HALF HOUR
HARDNESS - Rc
52
48
44
40
36
32
0
1
2
3
4
5
6
7
8
9
AGING TIME - HOURS
700 F
600 F
900 F
1100 F
500 F
400 F
400 F AGE
600 F AGE
900 F AGE
1100 F AGE
500 F AGE
700 F AGE
1000 F AGE (CURVE NOT DRAWN FOR THESE POINTS)

Figure 6

HEAT TREATMENT RESPONSE CURVES FOR TI-6AL-6V-2SN ALLOY WELD METAL

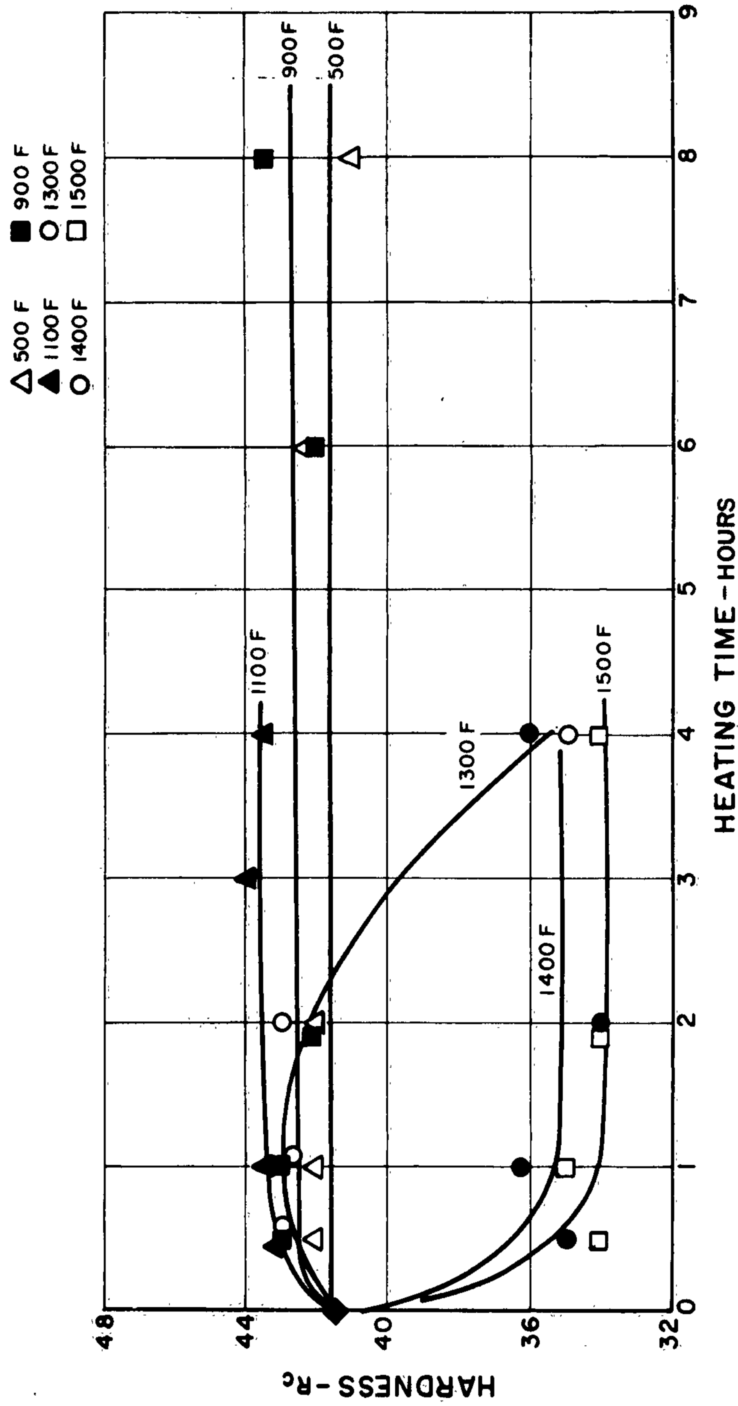


Figure 7

TENSILE PROPERTIES (70 F) OF 14-INCH DIAMETER SUBSCALE RING NUMBER 10 FLOW-TURNED BY THE PRESENT TWO-PASS TECHNIQUE (50 % REDUCTION PER PASS), STRESS-RELIEVED 850 F (1/2) AC AND AGED AT 800 F.

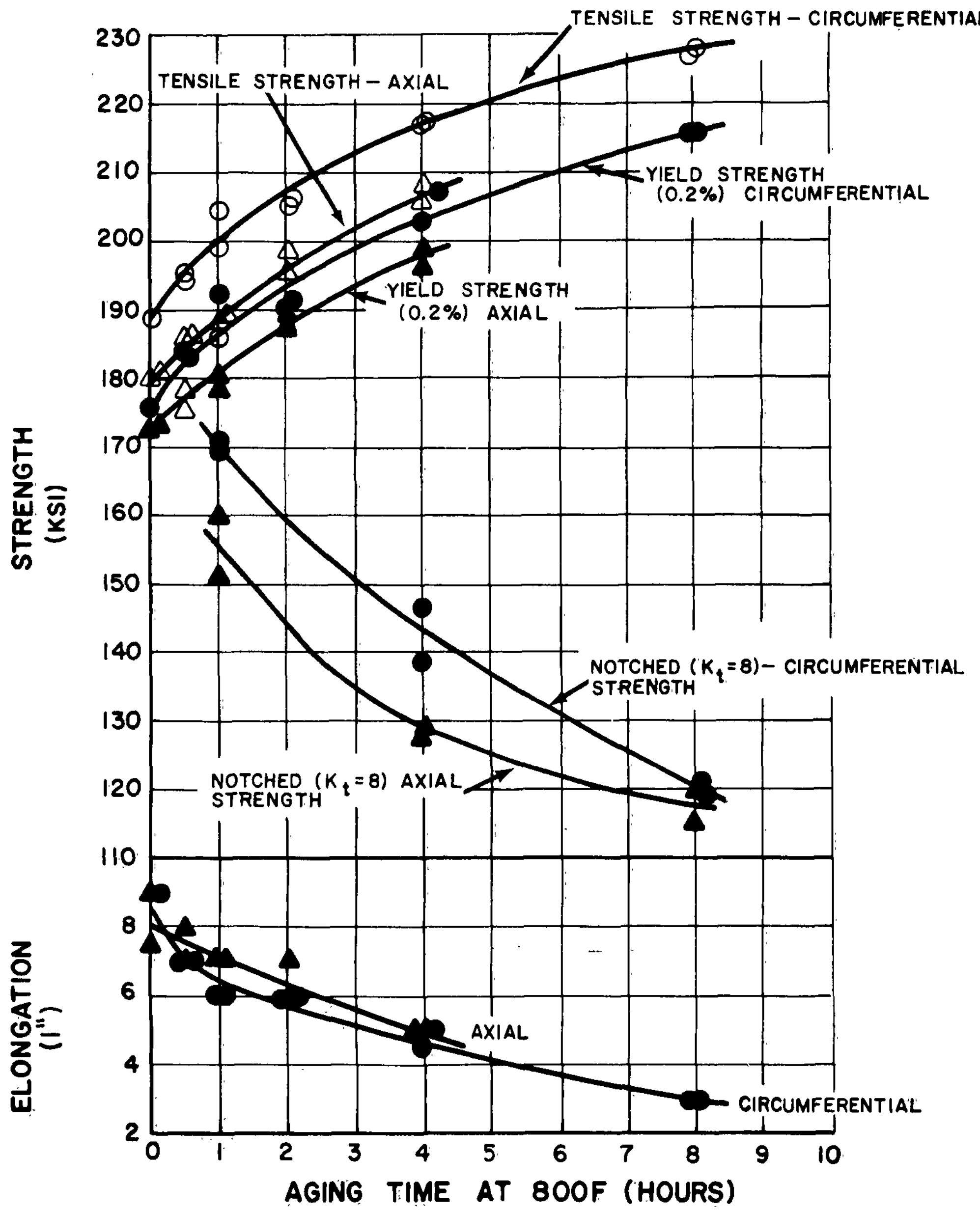


Figure 8

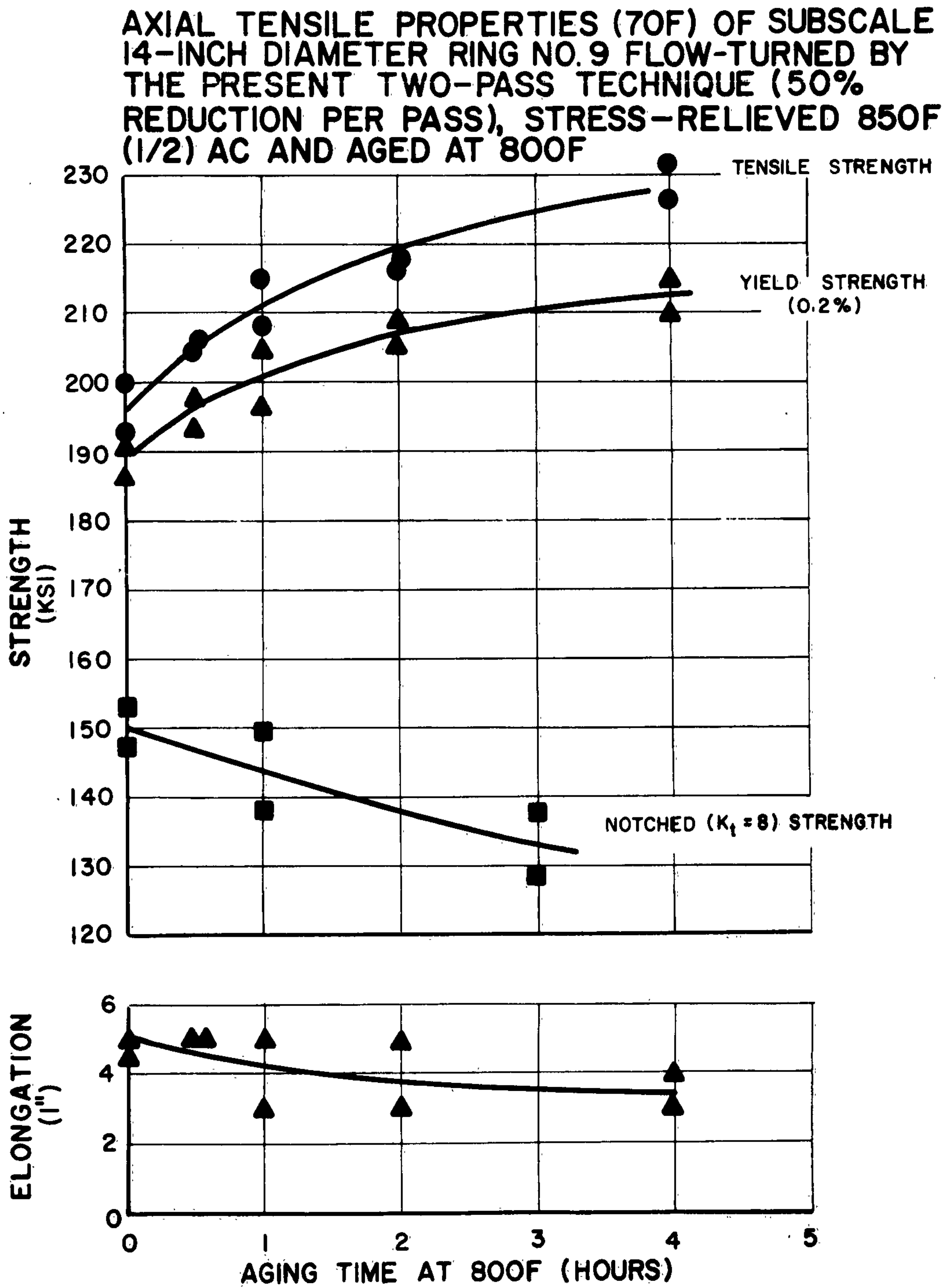
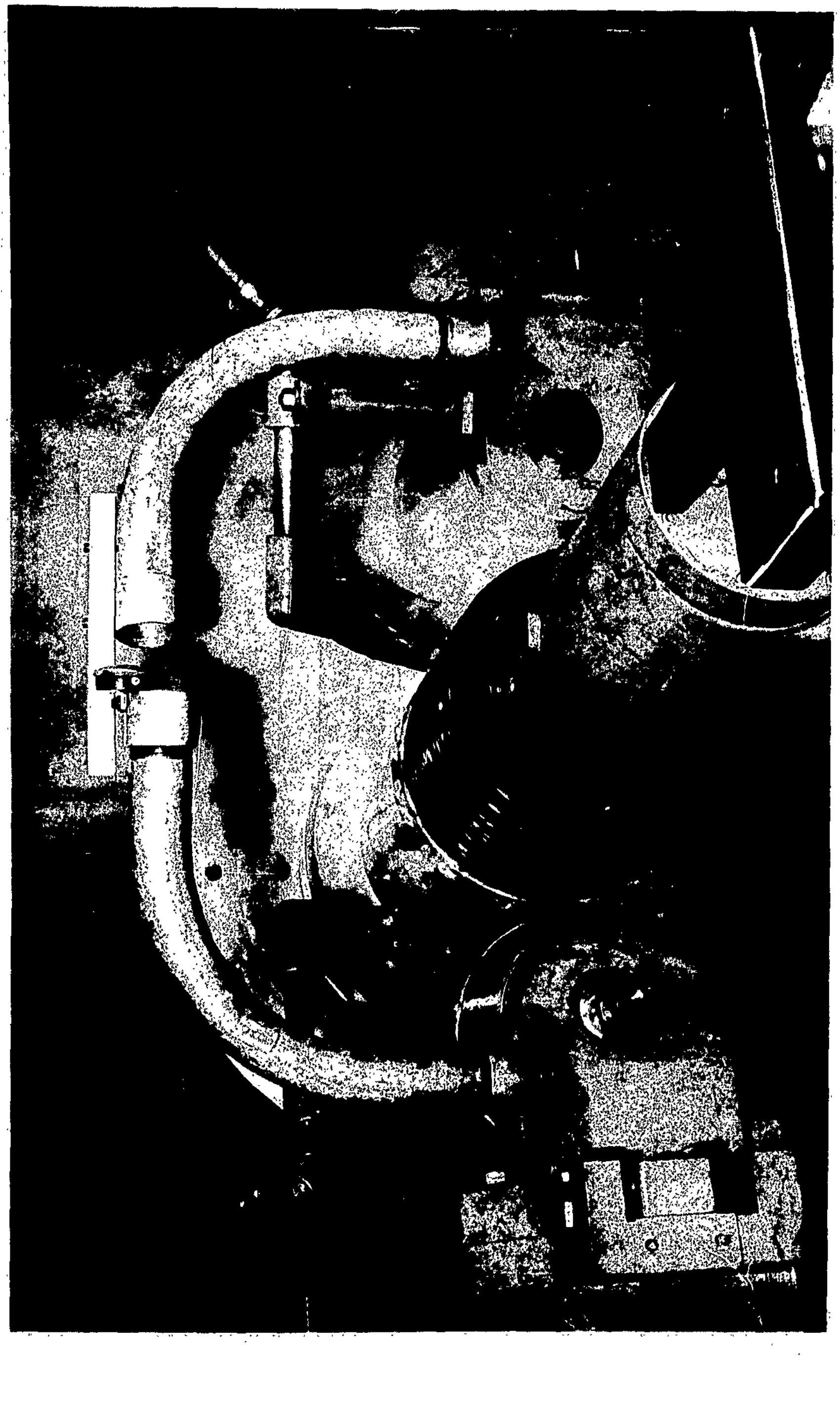

AXIAL TENSILE PROPERTIES (70F) OF SUBSCALE 14-INCH DIAMETER RING NO. 9 FLOW-TURNED BY THE PRESENT TWO-PASS TECHNIQUE (50% REDUCTION PER PASS), STRESS-RELIEVED 850F (1/2) AC AND AGED AT 800F
TENSILE STRENGTH
YIELD STRENGTH (0.2%)
NOTCHED (K_t = 8) STRENGTH
STRENGTH (KSI)
230
220
210
200
190
180
170
160
150
140
130
120
ELONGATION (1")
6
4
2
0
0
1
2
3
4
5
AGING TIME AT 800F (HOURS)

Figure 9



FLOW-TURNING OF 14-INCH B-120 VCA TITANIUM ALLOY CYLINDER
USING BRIDGING DEVICE TO MONITOR ROLLER SYNCHRONIZATION

Figure 10

FORTY-INCH DIAMETER B-120 VCA TITANIUM CYLINDER AFTER FLOW-TURNING PREPARATORY TO TRIMMING

Figure 11

TENSILE PROPERTIES (70F) OF FULL SCALE 40-INCH DIAMETER FLOW-TURNED CYLINDER NO. 2 FLOW-TURNED BY THE PRESENT TWO-PASS TECHNIQUE (50% REDUCTION PER PASS), STRESS-RELIEVED 850F (1/2) AC AND AGED AT 800F

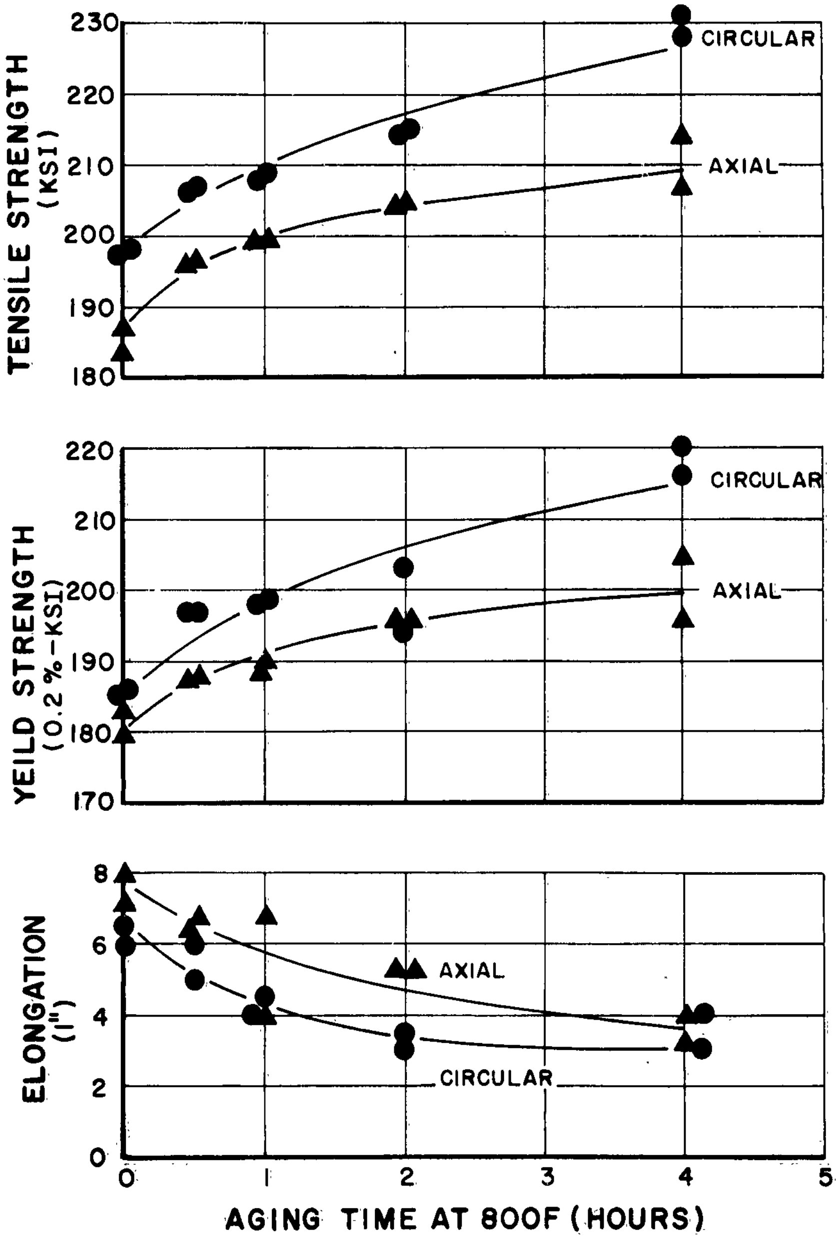
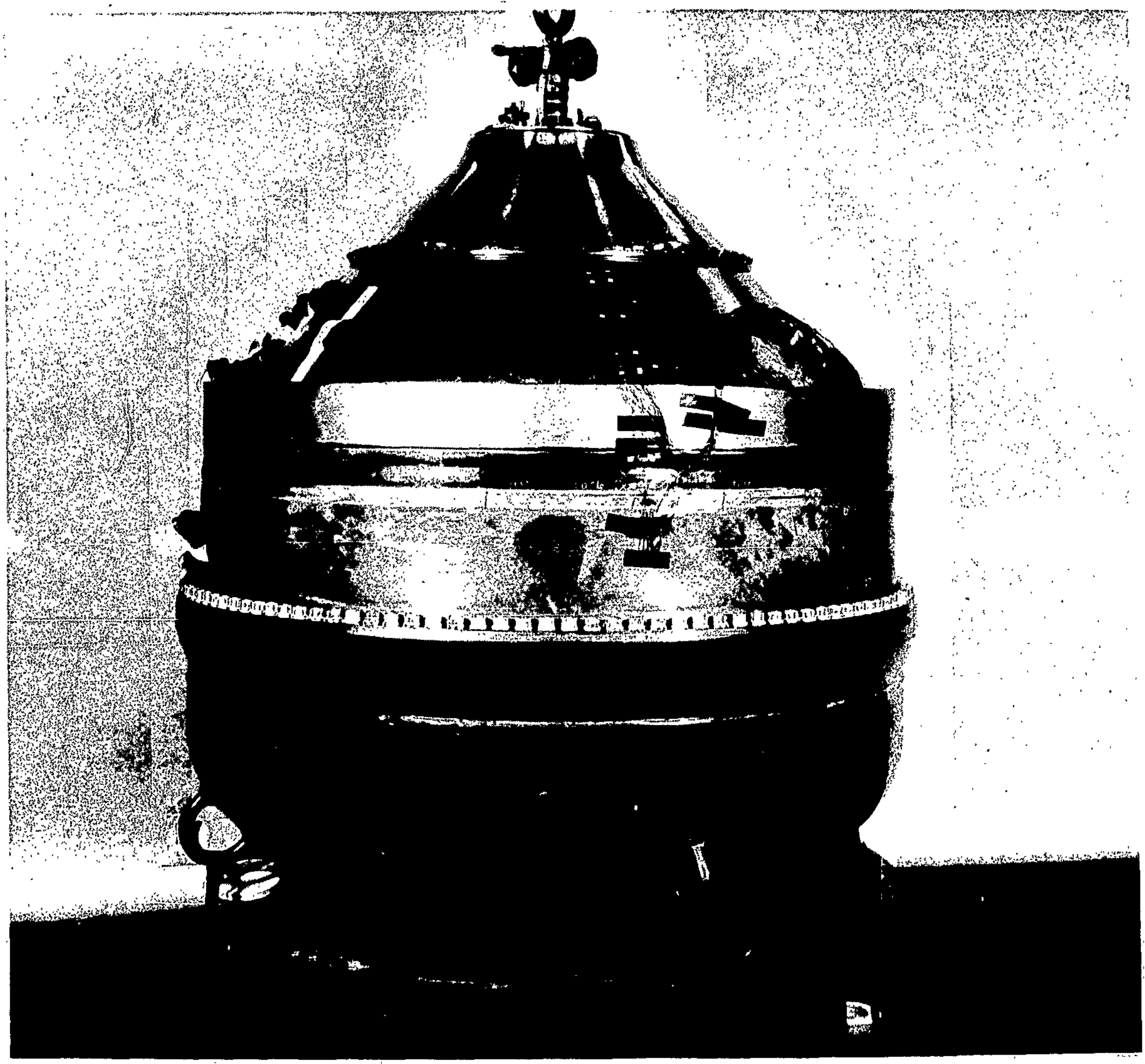
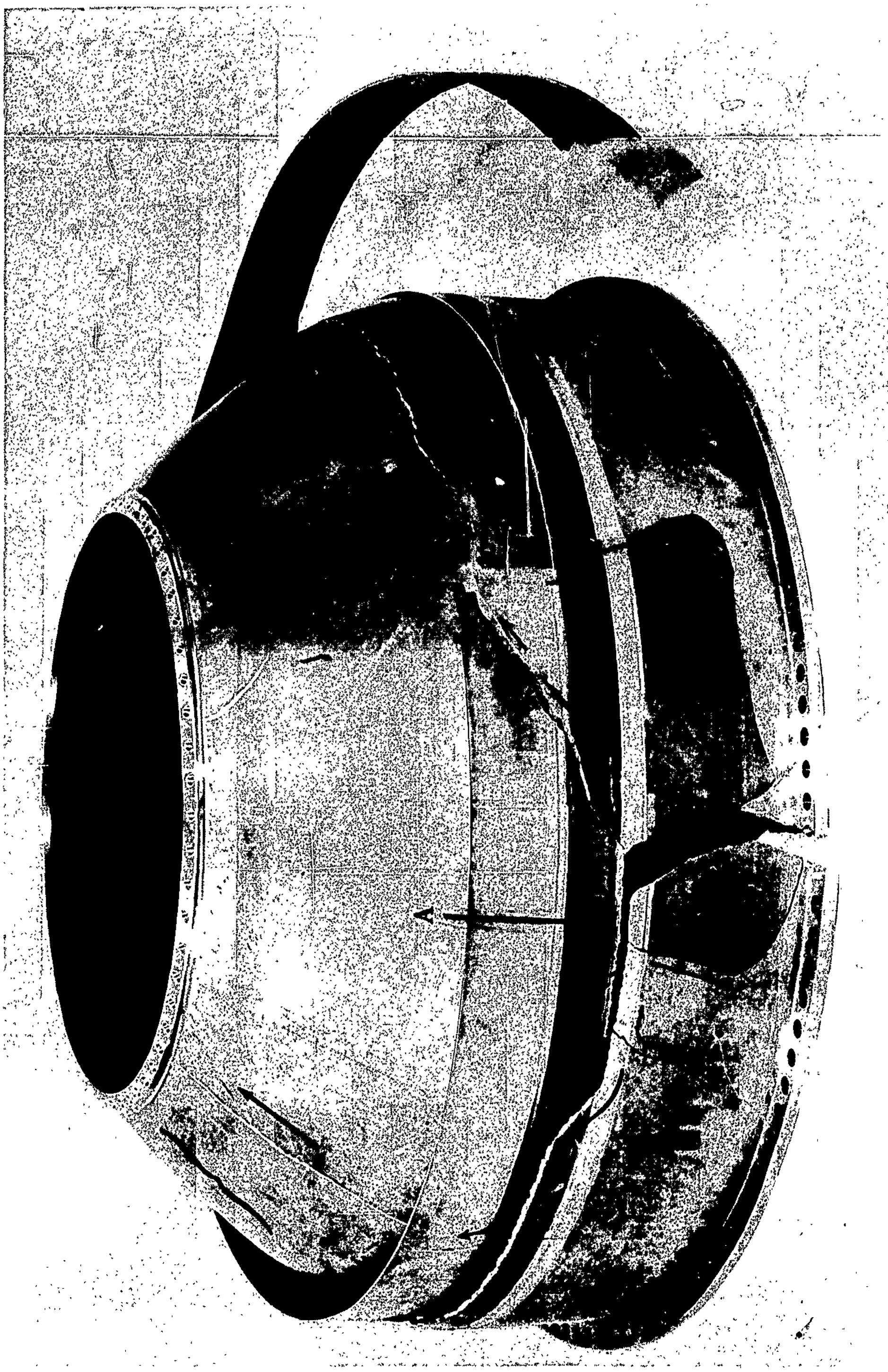


Figure 12



B-120 VCA TITANIUM 40-INCH DIAMETER REAR DOME COMPONENT ASSEMBLY FOR HYDROSTATIC TESTING

Figure 13



MAG: 1/6X

FULL SCALE REAR DOME ELA-6 WHICH BURST AT 1184 PSIG DURING HYDROSTATIC TESTING TO FAILURE. CURVED TORUS SECTION (BRACKETS) INDICATES THAT EXTENSIVE YIELDING OCCURRED PRIOR TO FAILURE. ARROW A INDICATES APPROXIMATE ORIGIN OF FAILURE. OTHER ARROWS SHOW DIRECTION OF CRACK PROPAGATION

Figure 14

FULL SCALE REAR DOME BURST TEST COMPONENT ELA-6 WHICH FAILED AT 1184 PSIG SHOWING FAILURE ORIGIN (ARROW A), MANUAL REPAIR WELD (BRACKET), AND DIRECTION OF CRACK PROPAGATION (ARROWS)

MAG: 1/3X

Figure 15

MAG: 12X

FRACTURE SURFACES OF REAR DOME BURST TEST COMPONENT SHOWING APPROXIMATE ORIGIN OF FAILURE ON INSIDE SURFACE AT EDGE OF MANUAL REPAIR WELD (ARROWS)

Figure 16

MAG: 5X

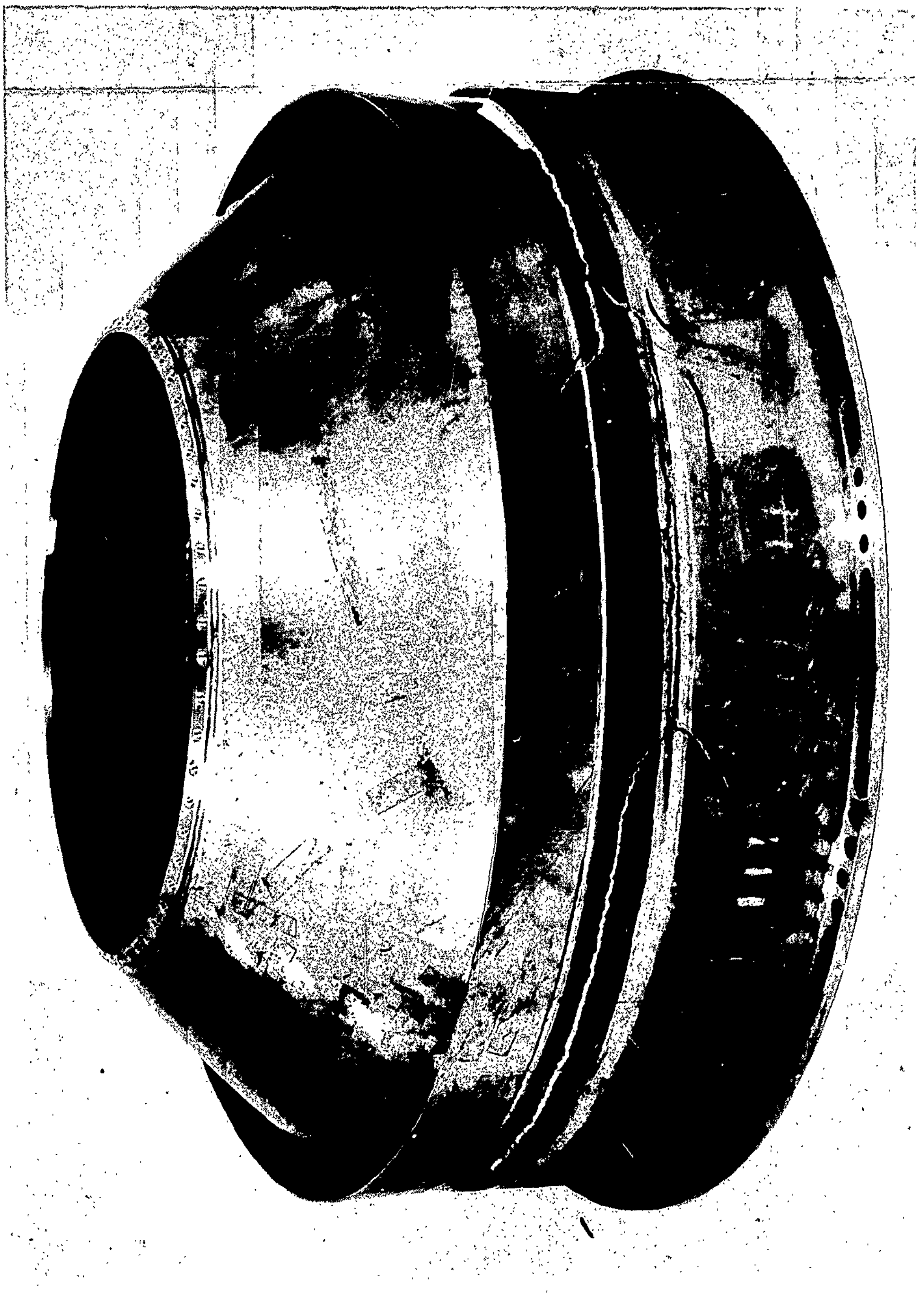
FRACTURE SURFACE OF REAR DOME BURST TEST COMPONENT SHOWING FAILURE IN HEAVY SECTION OF DOME NEAR CIRCUMFERENTIAL WELD. NOTE RELATIVELY BRITTLE APPEARANCE WITH TENDENCY TOWARD INTERANGULAR FAILURE

Figure 17

MAG: 10X

FRACTURE SURFACE OF REAR DOME BURST TEST COMPONENT SHOWING DUCTILE FAILURE (100 PER CENT SHEAR) IN THIN SECTION OF DOME MEMBRANE

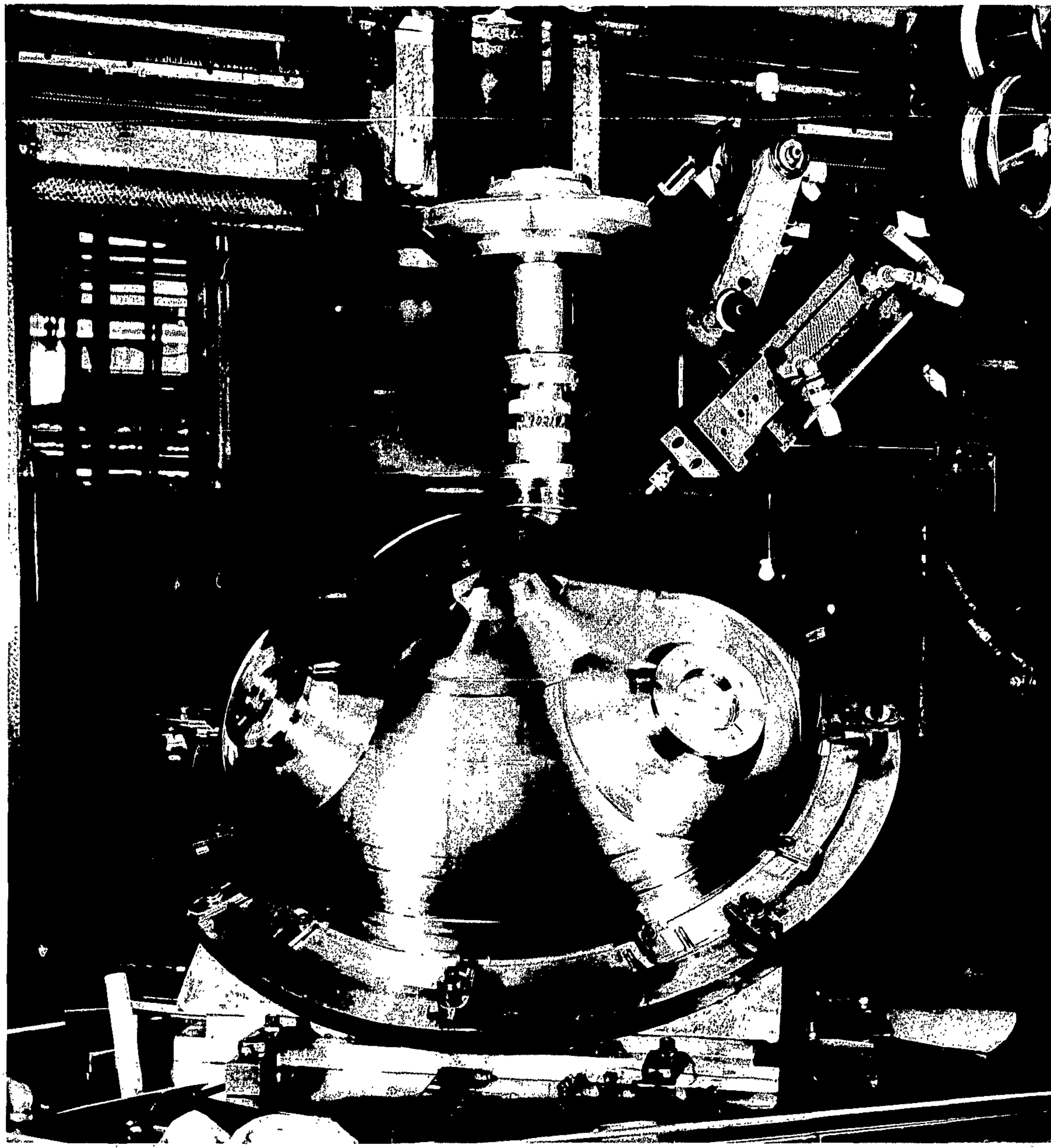
Figure 18



MAG: 1/6X

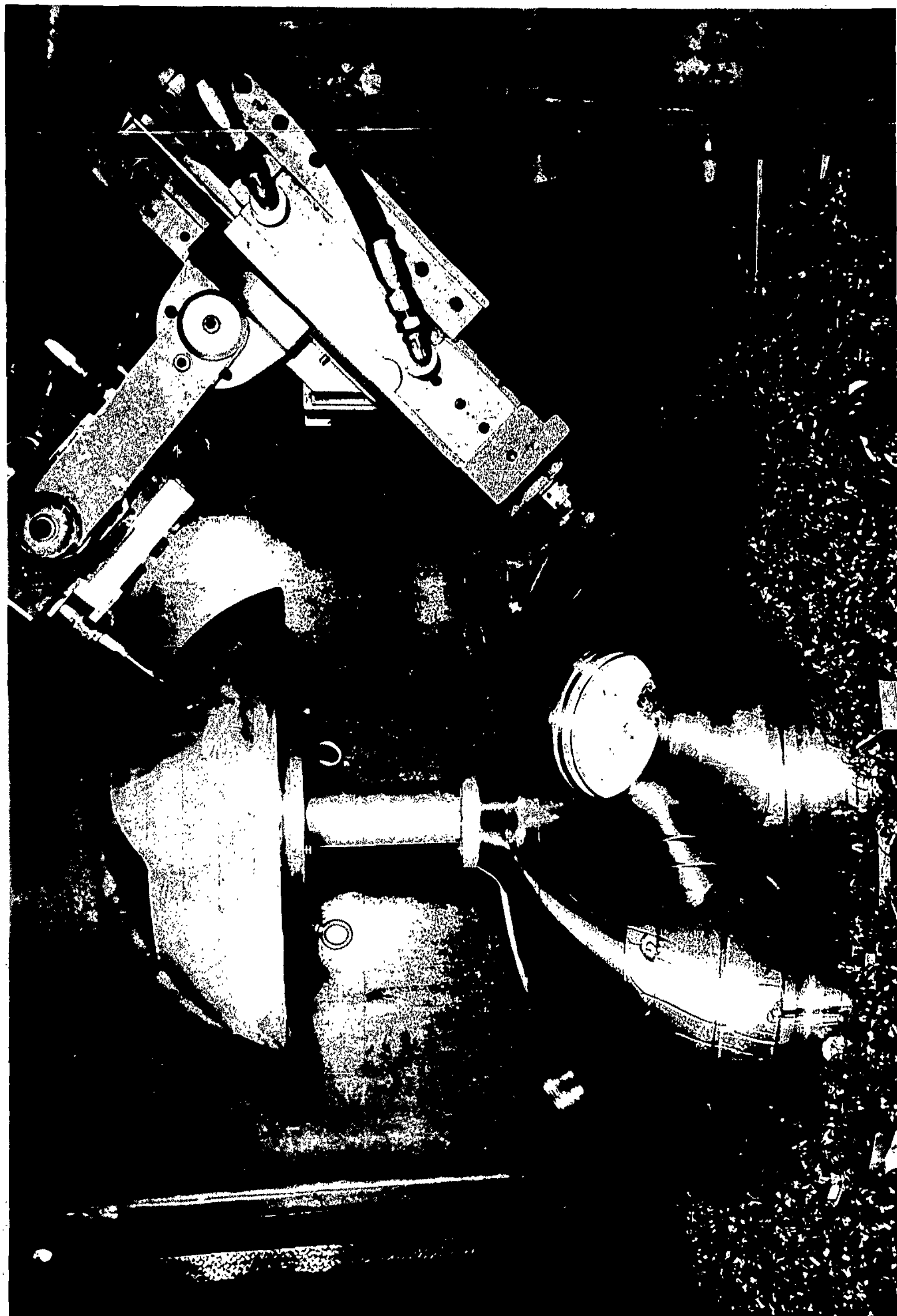
FULL SCALE REAR DOME BURST TEST COMPONENT ELA-6 AFTER FAILURE IN HYDROSTATIC TEST SHOWING CRACK PROPAGATION (ARROWS) ALONG EDGE OF MANUAL REPAIR WELD (BRACKET)

Figure 19



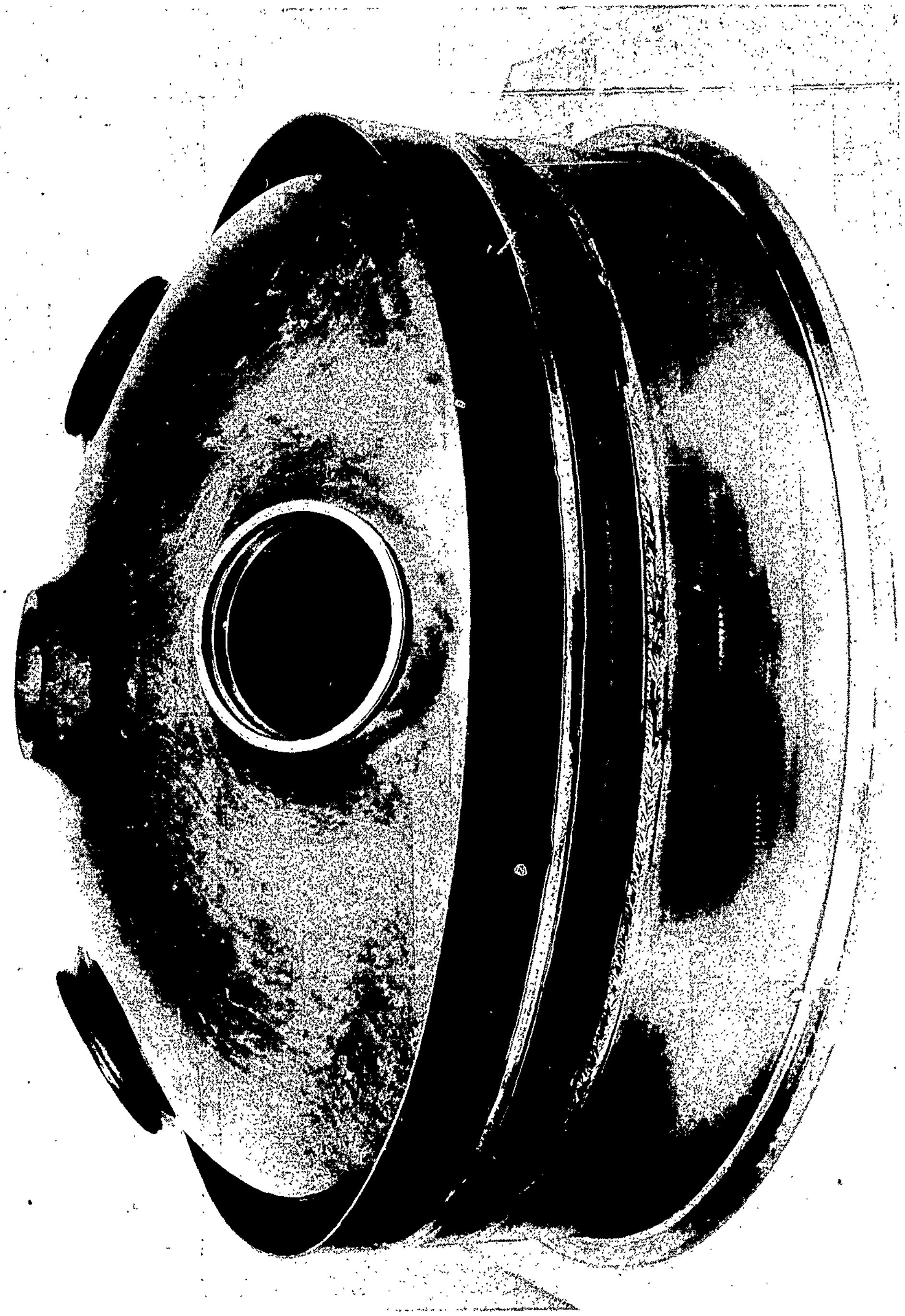
FINAL RISE-AND-FALL MACHINING OF B-120 VCA TITANIUM ROCKET MOTOR CASE FORWARD DOME

Figure 20



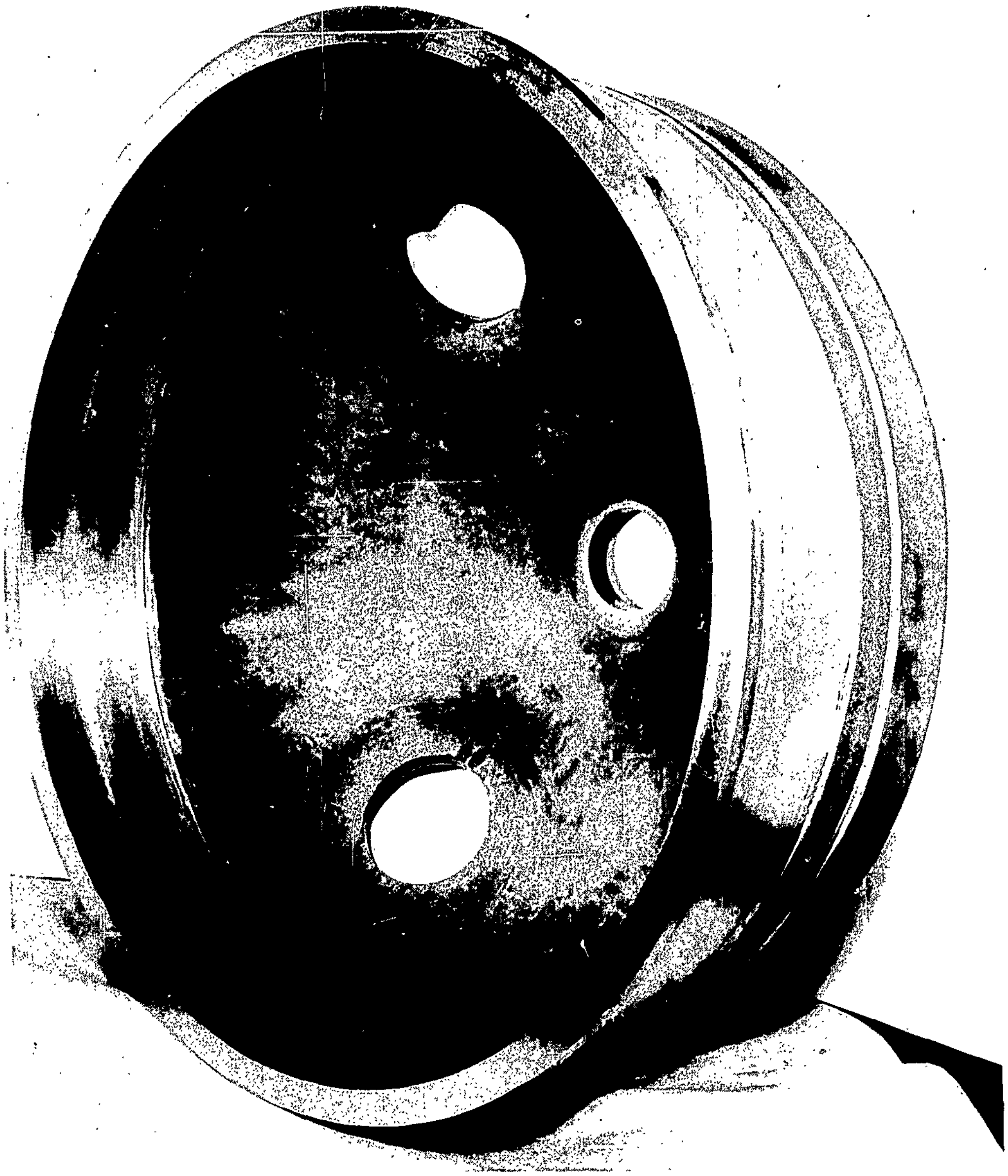
SKIP TURNING OUTER CONTOUR OF B-120 VCA TITANIUM ROCKET
MOTOR CASE FORWARD DOME

Figure 21



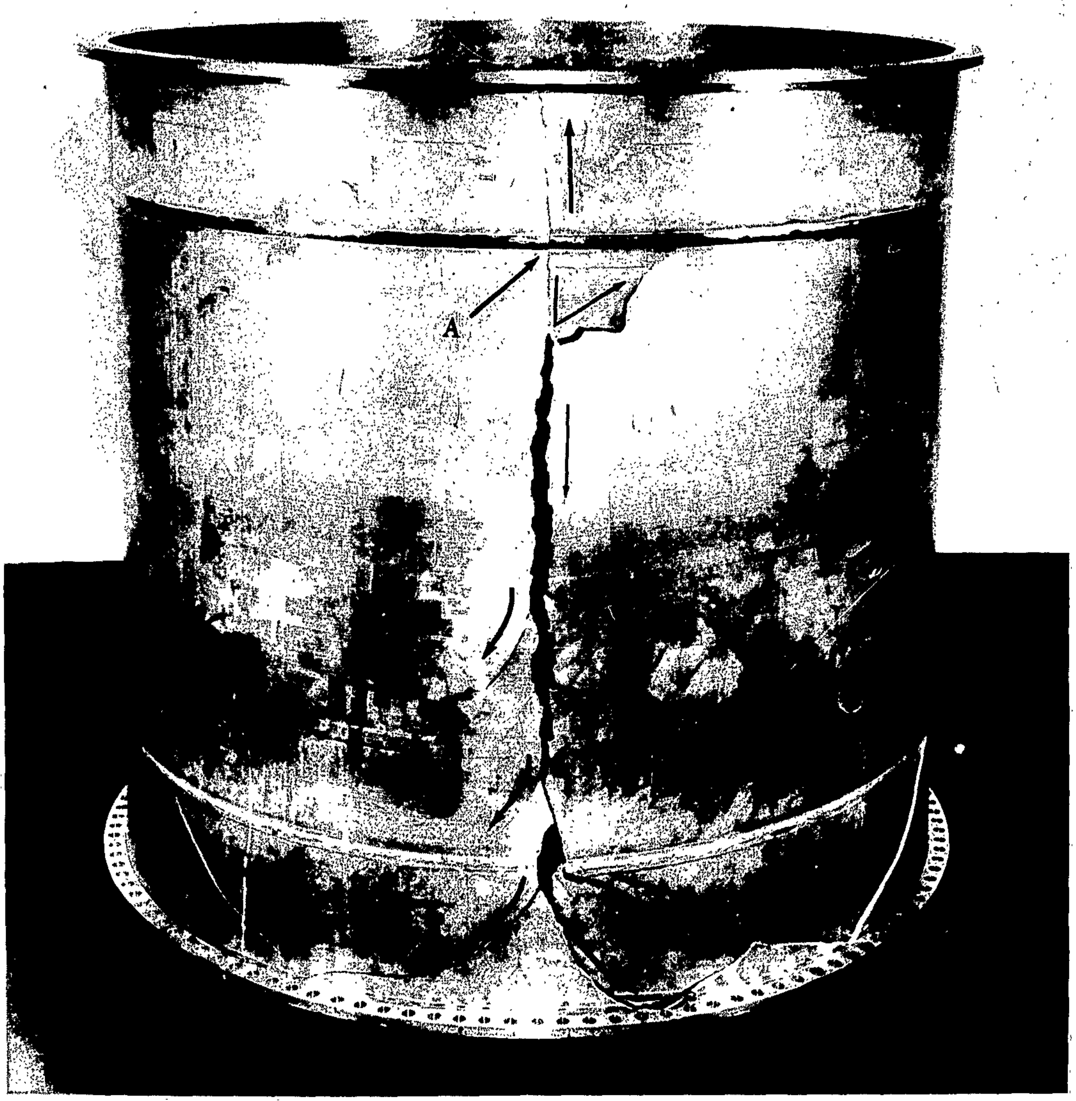
FRONT DOME ELA-5 AND BURST TEST ADAPTER WELDMENT.
B-120 VCA TITANIUM ALLOY

Figure 22



FRONT DOME ELA-5 AND BURST TEST ADAPTER WELDMENT, B-120 VCA TITANIUM ALLOY

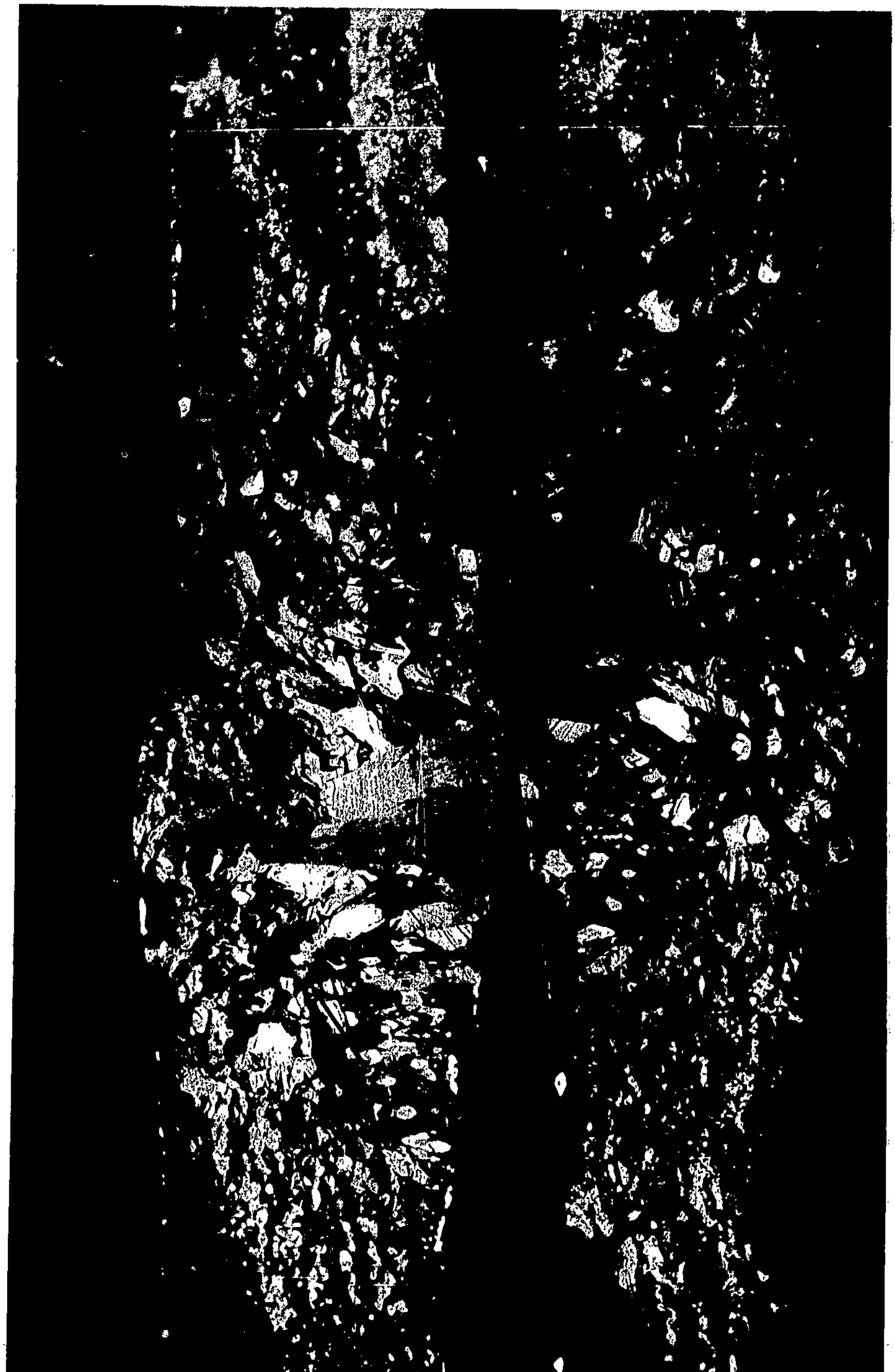
Figure 23



MAG: 1/8X

FIRST FULL SCALE FLOW-TURNED CENTER SECTION BURST TEST COMPONENT WHICH FAILED AT 540 PSIG WITH FAILURE ORIGIN IN CIRCUMFERENTIAL WELD (ARROW A). ARROWS SHOW DIRECTION OF CRACK PROPAGATION

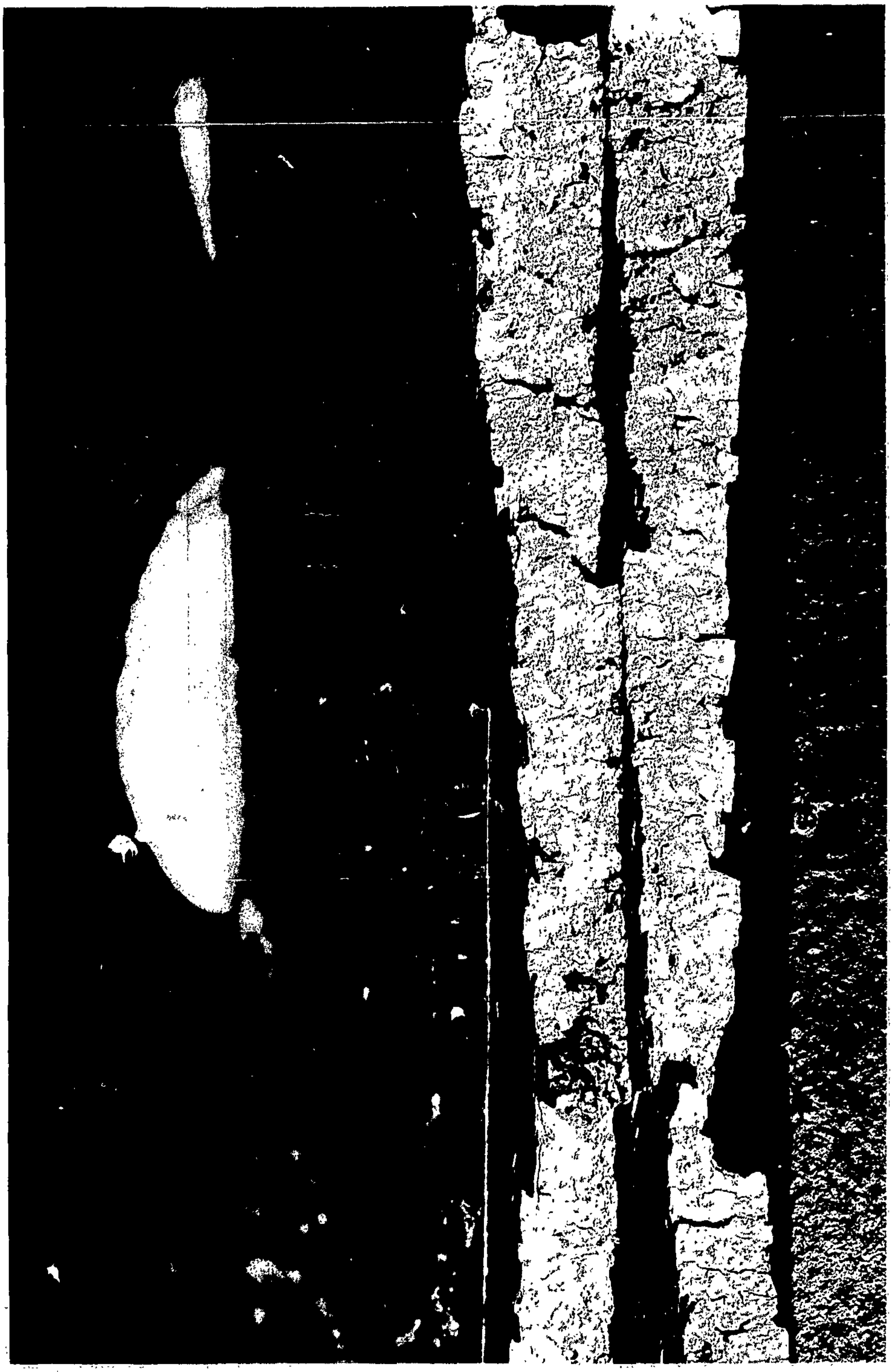
Figure 24



FRACTURE SURFACES OF CYLINDER BURST TEST COMPONENT SHOWING ORIGIN OF FAILURE AT CIRCULAR PREVIOUS CRACK (BRACKETS) THROUGH POROSITY PORE (ARROWS) IN CIRCUMFERENTIAL CYLINDER-TO-ADAPTER WELD

MAG: 12X

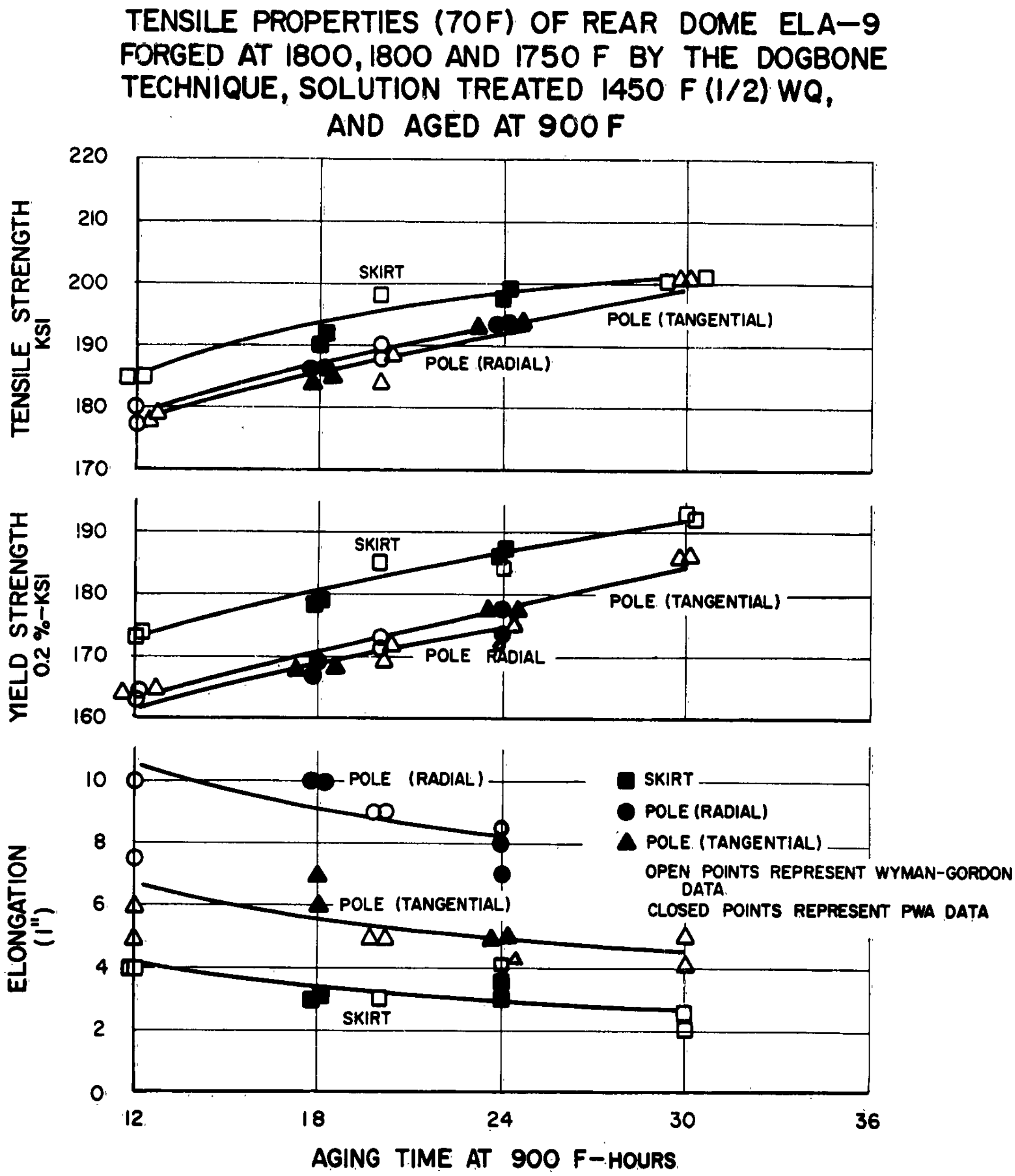
Figure 25



MAG: 9X

FRACTURE SURFACES OF CYLINDER BURST TEST COMPONENT SHOWING DUCTILE (100 PER CENT SHEAR) FAILURE IN FLOW-TURNED CENTER SECTION

Figure 26



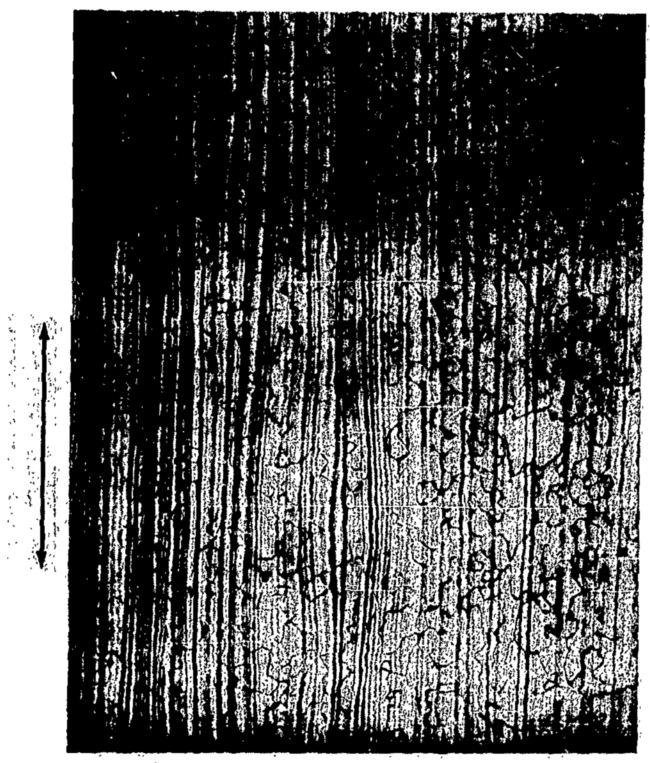
TENSILE PROPERTIES (70F) OF REAR DOME ELA-9 FORGED AT 1800, 1800 AND 1750 F BY THE DOGBONE TECHNIQUE, SOLUTION TREATED 1450 F (1/2) WQ, AND AGED AT 900 F
TENSILE STRENGTH KSI
YIELD STRENGTH 0.2 %-KSI
ELONGATION (1")
SKIRT
POLE (TANGENTIAL)
POLE (RADIAL)
POLE RADIAL
SKIRT
POLE (RADIAL)
POLE (TANGENTIAL)
OPEN POINTS REPRESENT WYMAN-GORDON DATA
CLOSED POINTS REPRESENT PWA DATA
AGING TIME AT 900 F-HOURS
12
18
24
30
36

Figure 27

Etchant: 5% HF, 35% HNO_3 Mag: 1000X

Typical microstructure in polar area of rear dome ELA-9 solution treated at 1450F and aged at 900F for 18 hours. Note the coarse lamellar aging constituent

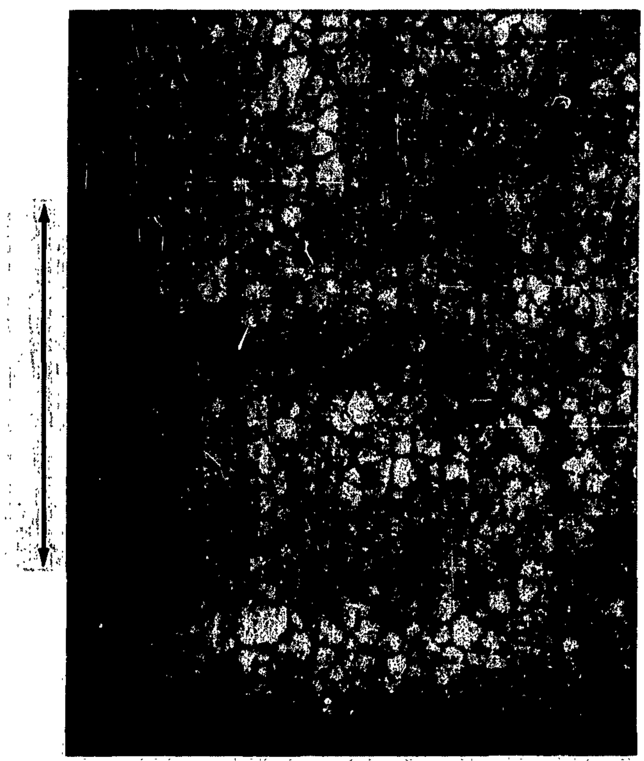
Figure 28



ETCHANT: LACTIC ACID, HNO_3, HF MAG: 100X

TYPICAL MICROSTRUCTURE OF TI-15 MO ALLOY SHEET IN SOLUTION TREATED (1508F) CONDITION. NOTE EQUIAXED GRAIN STRUCTURE AND BANDING. MILL ROLLING DIRECTION IS INDICATED BY ARROW

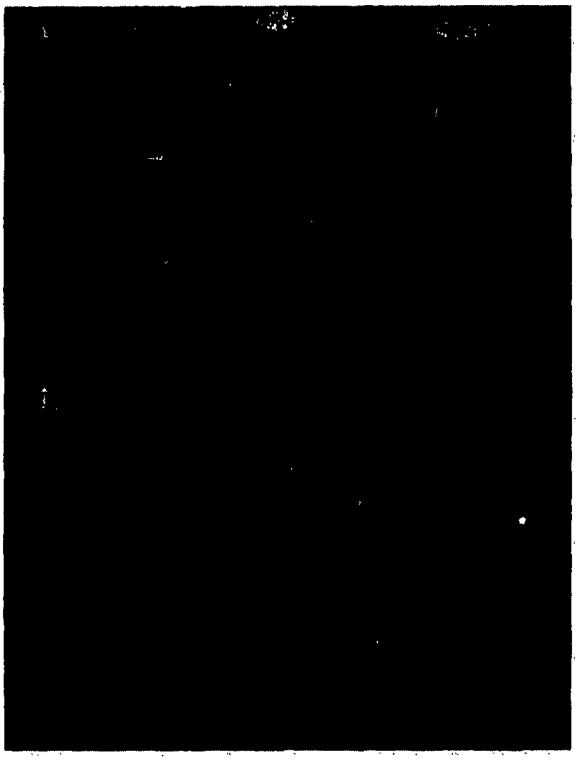
Figure 29



ETCHANT: LACTIC ACID, HNO_3 HF MAG: 100X

TYPICAL MICROSTRUCTURE OF TI-15MO ALLOY SHEET IN SOLUTION TREATED AND AGED CONDITION (1508F (1/2)WQ +977F (17) AC). NOTE EQUIAXED GRAIN STRUCTURE AND HEAVY GRAIN BOUNDARIES. MILL ROLLING DIRECTION IS INDICATED BY ARROW

Figure 30



Etchant: Lactic Acid, HNO_3 HF

Mag: 2000X

Typical microstructure of Ti-15Mo alloy sheet in solution treated and aged (1508F (1/2)WQ + 977F (16) AC) condition. Note the plate-like aging constituent emanating from grain boundaries and mottled matrix

Figure 31

Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford 8, Connecticut.
TENTH QUARTERLY REPORT ON RESEARCH AND DEVELOPMENT OF TITANIUM ROCKET MOTOR CASES, by H.A. Hauser and W.E. Helfrich, January 31, 1963. 75 p. incl. illus. Project No. TB4-004, Contract No. DA-19-020-ORD-5230.

Unclassified Report

The results of work performed during the quarter October 1 through December 31, 1962 on the research and development of a high strength, lightweight titanium alloy rocket case are reported. These results include
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1. Rockets, Motor Cases
2. Titanium Fabrication
3. Titanium Alloys

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II. U.S. Army Ordnance Corps Watertown Arsenal
III. Contract DA-19-020-ORD-5230

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I. Hauser, H.A. and Helfrich, W.E.
II. U.S. Army Ordnance Corps Watertown Arsenal
III. Contract DA-19-020-ORD-5230

1) Smooth and notched tensile properties of flow-turned material with hydrogen contents of 70 and 200 ppm, 2) results from cyclic loading and tensile testing of B-120 VCA titanium alloy TIG welds, 3) tensile and hardness data for Ti-6Al-6V-2Sn alloy TIG welds, 4) smooth and notched tensile data for 40-inch diameter roll-forged rings re-solution treated at 1800F, 5) smooth and notched tensile properties of 14- and 40-inch diameter flow-turned cylinders, 6) tensile properties of 40-inch diamter rear dome press-forged in closed dies at 1750F, 7) results from hydrostatically burst testing full scale component assemblies, one containing a flow-turned cylinder and the other a press-forged rear dome, and 8) bend and tensile test data for Ti-15 Mo alloy sheet stock.

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